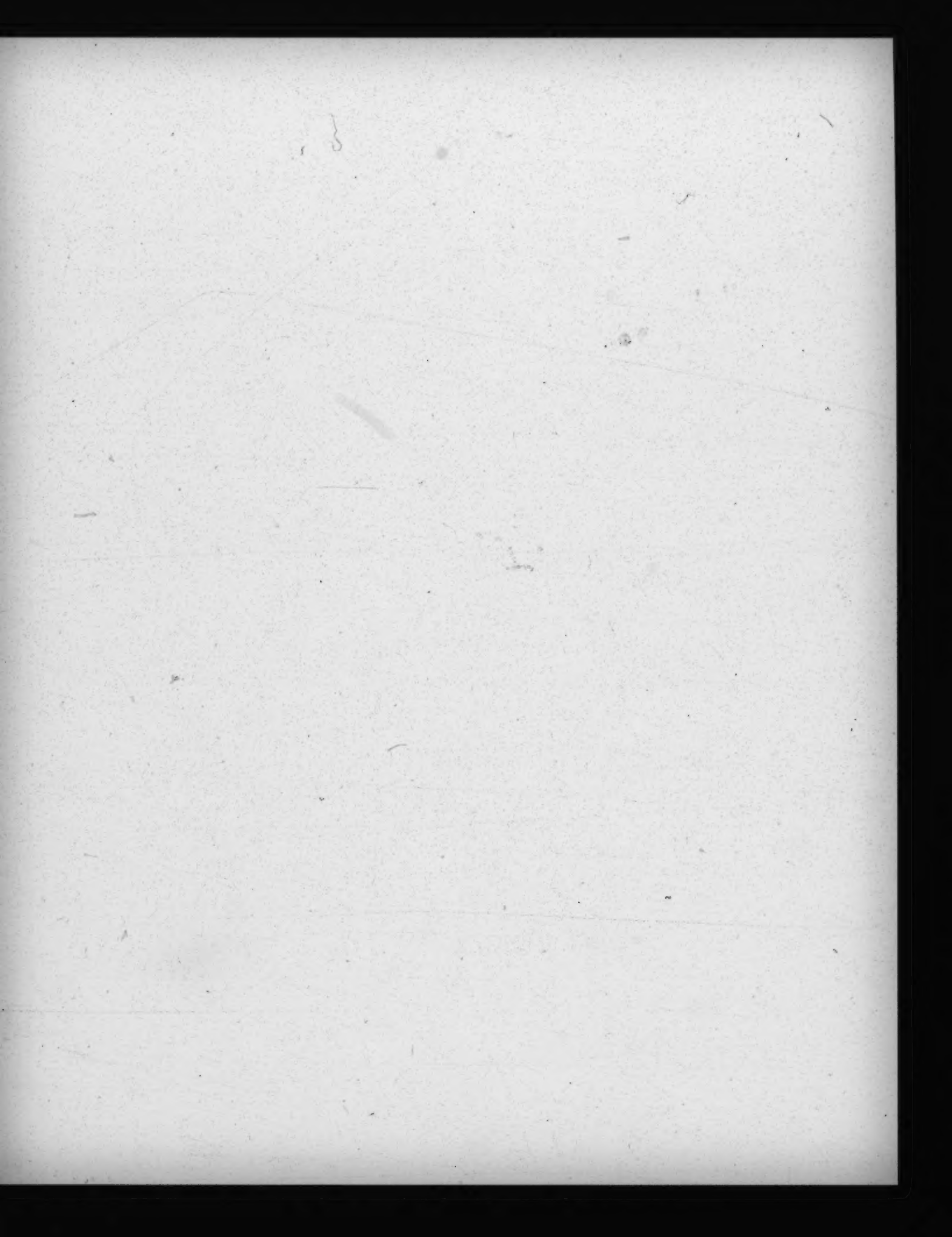


We do not inherit the earth from our parents.

We borrow it from our children.

— Native American saying



University of Alberta

Trace Metal Sources in Mixed Municipal Solid Waste Compost Systems

by

Bo Ge



A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science
in
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Abstract

This research mainly focused on the identification of sources of trace metals in mixed MSW compost systems. The trace metals of most concern in contaminant reduction programs were identified, which were Cd, Hg, Pb, Zn, As, Ni, Cu, Mo, Cr, and Se. Through a review of the literature on manufacturing and waste characterization studies, potential sources of trace metals in MSW were identified, which were non-compostables such as electronic products, batteries, and ferrous and non-ferrous metals. Biosolids could be a significant source of Cd, Co, Mo, Se, and Cr in MSW and biosolids co-composting systems. Composting mixing drums could contribute from 4.3% to 10.5% of the total Cu concentration in compost. The chemical analysis of paper and plastic samples from Edmonton Materials Recovery Facility indicated that coloured ink could be associated with Cu, but the impact of coloured ink on the Cu content of the samples was relatively minor.

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Nomenclature and Abbreviations

AB	Alberta
ANOVA	Analysis of Variance
ATSDR	Agency for Toxic Substances and Disease Registry
BC	British Columbia
BNQ	the Bureau de normalisation du Québec
CCME	the Canadian Council of Ministers of the Environment
C & D	Construction and demolition
CFA	the Canadian Fertilizers Act
CFIA	the Canadian Food Inspection Agency
ECF	Edmonton Composting Facility
HDPE	High density polyethylene
HHW	Household hazardous waste
IC & I	Institutional, commercial and industrial
LDPE	Low density polyethylene
MB	Manitoba
MENV	Ministère de l'Environnement du Québec
Mixed MSW	Non-source separated municipal solid waste, containing both biodegradable materials, e.g., food and paper, and non-biodegradable materials, e.g., plastics and glass.
MRF	Material recovery facility
MSW	Municipal solid waste
NB	New Brunswick

NF	Newfoundland & Labrador
NS	Nova Scotia
OME	Ontario Ministry of Environment
OMR	Organic Matter Recycling
ON	Ontario
PE	Prince Edward Island
PETE	Polyethylene terephthalate
PP	Polypropylene
PVC	Polyvinyl chloride
PS	Polystyrene
QC	Quebec
SK	Saskatchewan
TMECC	Test Methods for the Examination of Composting and Compost
Trace Metals	Metals and semimetals (metalloids) presenting in compost at a very low concentration, including arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), mercury (Hg), molybdenum (Mo), nickel (Ni), lead (Pb), selenium (Se), and zinc (Zn).
USEPA	the United States Environmental Protection Agency
WWTP	Wastewater treatment plant

Chapter 1 Introduction

1.1 Development of MSW Composting

Municipal solid waste (MSW) composting facilities are mainly classified into two categories – mixed MSW composting and source-separated organics composting (Goldstein 2005a). Mixed MSW is defined as non-source separated municipal solid waste, consisting of both compostable materials, e.g., food and paper, and non-compostable materials, e.g., plastics and glass. The mixed MSW stream theoretically excludes recyclables, but in practice no recycling programs can recycle 100% of recyclables. Thus, recyclables may end up in the mixed MSW stream. Mixed MSW composting refers to the composting of the non-source separated waste stream. Source-separated organics composting refers to the composting of organic wastes separated at their source.

It has been noticed that the term “MSW composting” has been sometimes used to refer to “mixed MSW composting” in both the literature and practice (Richard et al. 1993; Goldstein 2005a). To avoid confusion, the term “mixed MSW composting” is used in the current work to refer to non-source separated MSW composting, and “MSW composting” is used to refer to both mixed and source-separated MSW composting.

MSW composting has met with difficulties since it first occurred as an alternative MSW management option in 1925 (Hickman 2006). MSW composting plants appeared in the U.S. in the 1950s (Hickman 2006); however, few MSW composting facilities survived after the late 1960s (Haug 1993). MSW composting regained attention in the U.S. in the

late 1980s due to the success of MSW composting in Europe, the Middle East, and South America (Haug 1993). The amount of MSW composting has been increasing in the past decade (Goldstein 2005a). Figure 1-1 presents the number of operating MSW composting facilities in the U.S. over the last 10 years. The figure indicates that there has been a growing trend in the U.S. in adopting mixed and source-separated MSW composting as a MSW management option since 1997. Whether or not MSW composting can thrive in the future is a question to be answered.

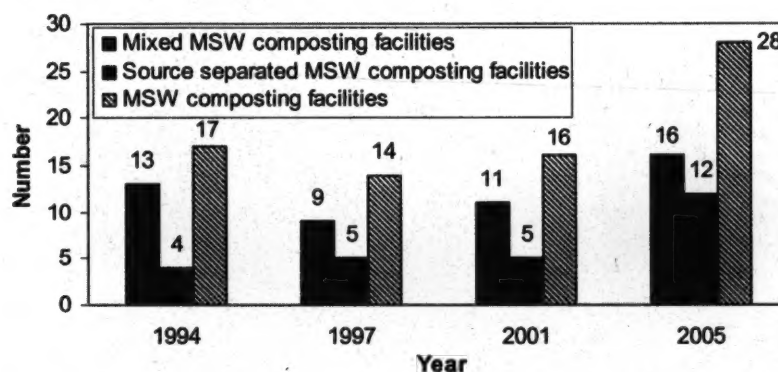


Figure 1-1. Operating MSW composting facilities in the U.S. from 1994 to 2005. Data sources: Hickman (2006), Glenn (1997), Satkofsky (2001), Goldstein (2005a), Goldstein (2005b).

1.2 Challenges for Mixed MSW Composting Facilities

Mixed MSW composting facilities are facing two challenges – poor quality end-products and lack of markets (Hickman 2006). Poor quality end-products are related to the contamination of composted materials. Compost markets are directly related to compost quality (Heath 2006). The composting facilities need to solve these problems in order to survive.

Poor quality of compost resulted partially from the shredding of the incoming MSW in old types of composting facilities (Goldstein 2005a). Shredding led to contamination of composted materials. However, new types of facilities now use rotary drums to gently open garbage bags to reduce contamination. The refining stage is also enhanced in new facilities to improve the quality of compost.

Composts having high foreign matter or trace metal content are sometimes not accepted in the market because of aesthetic or health concerns. The majority of the mixed MSW composting facilities in the U.S. have closed due to lack of markets (Vesilind et al. 2002).

1.3 Edmonton Composting Facility

The Edmonton Composting Facility (ECF) is the largest MSW composting plant in North America. The ECF has been in operation for about six years since it began its operation in March 2000. The facility occupies an area of 38,690 m², about the size of eight football fields (EWMC 2006). It is a co-composter, capable of processing 200,000 tonnes of residential waste and 22,500 dry tonnes of sewage biosolids annually (EWMC 2006). It can produce approximately 80,000 tonnes of compost each year (EWMC 2006). The ECF compost meets the Canadian Council of Ministers of the Environment (CCME) Category B compost criteria.

As a "trend-setting" project, the Edmonton Composting Facility was designed based on science and engineering, i.e. analyzing alternatives and making specific decisions process by process rather than relying on a single vendor with a turnkey system (Holden 2000).

The ECF is also operated and maintained by experienced staff (Goldstein 2000). All these ensure an economical and environmental success of the ECF (Goldstein 2000) and make the ECF a great case facility for mixed MSW composting.

1.3 Driving Forces on Mixed MSW Composting

The recent upsurge in mixed MSW composting is probably due to the following driving forces – increasingly stringent regulations, landfill limitations, technology advancements, and successful operations of existing facilities. These driving forces have made mixed MSW composting become more viable than previously.

Regulatory interest in recycling and diverting the organic fraction of MSW are increasing because this organic fraction can result in groundwater contamination and landfill gas problems. Many jurisdictions have established organics diversion goals. For example, Ontario has set a goal of diverting 60% of its MSW from disposal by the end of 2008 (MOE 2004). As a result of such planning, composting is becoming an alternative to landfilling.

The capacity of landfills has declined in many communities (USEPA 1994). However, the generation rate of MSW and the need to handle MSW have increased (USEPA 1994). Finding sites for new landfills is becoming increasingly difficult in some municipalities (USEPA 1994). The difficulty may result from lack of either environmental or economic feasibility. An alternative to landfilling is needed as existing landfills are reaching their

capacities. Composting is becoming more attractive because it can be more economical than landfilling in some communities.

Technological advancements in composting make it possible to continually improve compost quality. For example, the application of rotary drums can greatly reduce contamination of composted materials. Enhanced refining processes can minimize contaminants in compost products. Novel technologies are being developed to satisfy the needs of mixed MSW composting.

Some existing facilities have been operating successfully for more than ten years (Heath 2006). The Edmonton Composting Facility, the largest of its type in North America, has been producing marketable products since 2000. The success of these facilities has encouraged more jurisdictions to move to mixed MSW composting.

1.4 Trace Metals in Mixed MSW Compost

High trace metal content in compost is an important issue that needs to be addressed in mixed MSW composting. Although the adoption of new composting technologies has reduced the trace metal levels in mixed MSW compost products, the metal content in mixed MSW compost is still higher than in composts produced from yard waste and source-separated organics (Richard and Woodbury 1994; Ge et al. 2005). The higher metal content in mixed MSW compost can lower the classification of the compost and have a negative impact on the application rate of the compost. High trace metal content

may negatively affect social acceptability and economic value of compost (Genevini et al. 1997) and become a barrier in the development of mixed MSW composting.

1.5 Focus of the Research

A project is being carried out to investigate the impact of pre-treatment on the quality of mixed MSW compost. The goal of the project is to find the lowest practical levels of trace metals that mixed MSW compost can reach. This research was the first phase of the project.

The purposes of the research were to: (1) understand the Canadian compost standards for trace metals, (2) identify priority trace metals in contaminant reduction programs, (3) identify the sources of trace metals in mixed MSW compost systems, and (4) analyze the trace metal content of feedstock materials, compost, and foreign matter (sorted out from compost).

(1) Canadian Compost Standards

The health effects of trace metals were first reviewed. Canada-wide and provincial compost standards, regulations, and guidelines were then reviewed and were briefly discussed.

(2) Priority Trace Metals

Priority trace metals were identified by analyzing historical trace metal concentrations from the Edmonton Composting Facility.

(3) Trace Metal Sources

Sources of trace metals in mixed MSW compost systems were identified by reviewing and analyzing the literature on the manufacturing of consumer products and published data from waste audits. An attempt was made to develop a diagram for trace metal mass flows.

(4) Analysis of Trace Metal content

Feedstock materials were sampled and analyzed for trace metal content. Compost fractions of various particle sizes and foreign matter sorted out from Edmonton MSW compost were also analyzed for trace metal content.

1.6 Summary and Conclusions

- A growing trend of adopting mixed MSW composting as a MSW management option has appeared over the past decade. The upsurge in mixed MSW composting is probably due to four driving forces – increasingly stringent regulations, landfill limitations, technology advancements, and successful operation of existing facilities. Mixed MSW composting is becoming more viable than ever.
- One of the challenges that mixed MSW composting facilities have to face is high trace metal content in mixed MSW compost. The high metal content can have a negative impact on classification, application rates, social acceptability, and the economic value of the mixed MSW compost.
- An investigation of the impact of pre-treatment on the quality of mixed MSW compost is being carried out, aimed at finding the lowest practical levels of trace

metals that mixed MSW compost can reach. This research was the first phase of the project. Four tasks were accomplished: reviewing Canadian compost standards for trace metals, identifying priority trace metals in contaminant reduction programs, identifying the sources of trace metals in mixed MSW compost systems, and analyzing trace metal content of feedstock materials, compost, and foreign matter.

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Chapter 2 Health Effects Associated with Trace Metals and Compost

Environmental Protection Standards

2.1 Introduction

Metals and semi-metals (metalloids) may be present in compost at a very low level as a result of composting materials containing them. These metals and semi-metals contained in compost are herein referred to as trace metals. Those of specific concern are arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), mercury (Hg), molybdenum (Mo), nickel (Ni), lead (Pb), selenium (Se), and zinc (Zn). Some of the trace metals, such as As, Co, Cr, Cu, Mo, Ni, Se, and Zn, are regarded as essential or beneficial to plants or animals (CCME 2005). However, the accumulation of trace metals in large quantities in soils over the long term may cause harmful effects on human health and the environment (CCME 2005).

Trace metals are an important factor to be considered in classifying compost products and evaluating compost environmental protection quality and thus are of regulatory concern. Environmental protection standards for compost are in place in Canada to protect humans and the environment. Compost standards ensure that composting is allowed to develop as an environmentally sound waste management solution.

This chapter presents summaries of the health risks posed by trace metals and compost environmental protection standards for trace metals in Canada. The impact of trace metal

concentrations and maximum acceptable cumulative metal additions to soil are discussed at the end of this chapter.

2.2 Health Effects Associated with Trace Metals

The toxic effects of trace metals are a widespread concern in modern industrialized societies in which trace metals are widely used. The health effects of trace metals are summarized in this section.

2.2.1 Health Effects Associated with Arsenic (Inorganic)

Arsenic (As) is one of the most toxic elements that can be found (Lenntech 2005a). Inorganic arsenic, considered more toxic than elemental arsenic and organic arsenic compounds, is of primary toxicological concern to humans (CCME 2003). Humans may be exposed to inorganic arsenic in ambient air, drinking water, soil, and food. The total daily intake of inorganic arsenic for Canadian adults and infants (fed a mixed diet) are approximately 0.18 and 0.73 $\mu\text{g kg}^{-1}$ body weight (bw) per day respectively (CCME 2003). The health effects of As are summarized in Table 2-1.

Table 2-1. Adverse health effects of inorganic As on humans.

	Information source	
	CCME (2003)	Lenntech (2005a)
Adverse effects	Carcinogenic: skin, bladder, kidney, and lung cancers. Noncancerous: skin and possibly peripheral vascular diseases, e.g., black foot disease.	Irritation of the stomach and intestines, decreased production of red and white blood cells, skin changes and lung irritation, infertility and miscarriages in women, skin disturbances, declined resistance to infections, heart disruptions, brain damage and DNA damage.

2.2.2 Health Effects Associated with Cadmium

It has been well-established that excess cadmium exposure has adverse health effects on humans (ICA 2005). Short-term exposure to cadmium has been related to a wide range of sub-lethal adverse effects on mammalian receptors. Acute gastroenteritis has been reported following dietary exposure to doses of 0.25–0.50 mg kg⁻¹ bw. The acute oral dose of cadmium in humans is estimated to be 5–500 mg kg⁻¹ bw. The health effects of Cd are summarized in Table 2-2.

Table 2-2. Adverse health effects of cadmium on humans and animals.

	Information source	
	CCME (2003)	Lenntech (2005b)
Adverse effects	Acute exposure: nausea, vomiting, diarrhea, muscular cramps, and salivation. Risk of cancer: no consistent evidence. Probably carcinogenic to humans. Cytogenetic alteration or DNA damage in mammalian cells, including those of humans. Teratogenicity and mutagenicity.	Kidney filtering mechanism damage

2.2.3 Health Effects Associated with Chromium

The health risks associated with exposure to chromium (Cr) are dependent on its oxidation state (Lenntech 2005c). According to Lenntech (2005c), chromium (III) is an essential nutrient for humans, but the uptake of too much Cr (III) can cause health problems, e.g., skin rashes. The hexavalent form of Cr is toxic. Due to the lack of information on the form of chromium in environmental media, it is impossible to make separate exposure estimates for Cr (III) and Cr (VI) (CCME 2003). The estimated daily intake refers to total chromium (CCME 2003). Adults, teenagers, school-aged children, preschoolers, and infants (assumed to be exclusively breast-fed) are estimated to be

exposed to 0.31, 0.43, 0.69, 1.43, and 0.22 $\mu\text{g Cr kg}^{-1}$ bw per day respectively (CCME 2003). The most important route of exposure is food, constituting 60% - 81% of the total daily estimated intake for all age groups except breast-fed infants (CCME 2003). The health effects of Cr are summarized in Table 2-3.

Table 2-3. Adverse health effects of chromium on humans.

		Information source	
		CCME (2003)	Lenntech (2005c)
Cr (III)	Suboptimal intake of Cr (III)	May lead to impaired glucose tolerance, elevated levels of circulating insulin, cholesterol, triglycerides, and an increased occurrence of aortic plaques.	NA
	Adverse effects	Unclassifiable with respect to carcinogenicity in humans	NA
Cr (VI)	Adverse effects	Carcinogenic to humans	Ulcerations, dermatitis, and allergic skin reactions. Ulceration and perforation of the mucous membranes of the nasal septum. Irritation of the pharynx and larynx. Asthmatic bronchitis, bronchospasms and edema. Weakened immune systems, kidney and liver damage, alteration of genetic material, and lung cancer.

NA – Not available

2.2.4 Health Effects Associated with Copper

Copper (Cu) is an essential nutrient incorporated into a number of metalloenzymes (ATSDR 2004a). The estimated total daily copper intakes for Canadians range from 22 to 74 mg kg^{-1} bw per day in adults and formula-fed infants respectively (CCME 2003). In spite of the copper homeostasis in the prevention of copper toxicity, the excessive

exposure to copper can result in adverse health effects (ATSDR 2004a). The health effects of Cu are summarized in Table 2-4.

Table 2-4. Adverse health effects of copper on humans.

	Information source	
	CCME (2003)	ATSDR (2004a)
Adverse effects	Fatal in humans if gram quantities of inorganic copper salts are ingested. Possibly mutagenic.	Liver and kidney damage, anemia, immunotoxicity, and developmental toxicity. Gastrointestinal distress.

2.2.5 Health Effects Associated with Lead

Lead (Pb) has no essential function in the human body and can be harmful after uptake from food, air or water (Lenntech 2005d). The health effects of Pb are summarized in Table 2-5.

Table 2-5. Adverse health effects of lead on humans.

	Information source	
	CCME (2003)	ATSDR (2004c)
Adverse effects	Severe effects on the central nervous system; intoxication with signs including dullness, restlessness, irritability, poor attention span, headaches, muscle tremor, hallucinations, and loss of memory; metabolic effects; tiredness, sleeplessness, irritability, headaches, and joint pain; genotoxic for some lead salts; gonadal and reproductive dysfunction; possibly carcinogenic to humans.	Anemia, severe kidney and brain damage, miscarriage and damage to organs responsible for sperm production.

2.2.6 Health Effects Associated with Mercury (Inorganic)

Mercury (Hg) is found in the environment mainly in the form of amalgams and inorganic salts. The U.S. Environment Protection Agency classified mercuric chloride as a possible human carcinogen. Inorganic mercury compounds have not been classified by Health

Canada with respect to human carcinogenicity. The health effects of Hg are summarized in Table 2-6.

Table 2-6. Adverse health effects of mercury (inorganic) on humans.

	Information source	
	CCME (2003)	NEWMOA (2005)
Adverse effects	The U.S. Environment Protection Agency classified mercuric chloride as a possible human carcinogen. Mercury-induced auto-immune glomerulonephritis.	Renal toxicity, skeletal muscle degeneration, gastrointestinal irritation, pulmonary edema, elevated blood pressure, low grade/intermittent fevers, flushing of palms

2.2.7 Health Effects Associated with Nickel

The International Agency for Research on Cancer (IARC) has listed nickel compounds within group 1 (i.e. there is sufficient evidence for carcinogenicity in humans) and nickel within group 2B (which are possibly carcinogenic to humans) (Lenntech 2005f). The health effects of Ni are summarized in Table 2-7.

Table 2-7. Adverse health effects of nickel on humans and animals (Lenntech 2005f).

	Humans	Animals
Adverse effects	higher chance of development of lung cancer, nose cancer, larynx cancer and prostate cancer; sickness and dizziness after exposure to nickel gas; lung embolism; respiratory failure; birth defects; asthma and chronic bronchitis; allergic reactions such as skin rashes; heart disorders.	Moderately toxic to mammals and birds.

2.2.8 Health Effects Associated with Selenium

Selenium (Se) is an essential trace element in animal and human nutrition (CCME 2003). Selenium has a small margin of safety between dietary deficiency levels of selenium compounds and the levels that result in toxicity (CCME 2003). Many manifestations of selenium toxicity are very similar to those of selenium deficiency (CCME 2003). The

recommended daily intake of selenium as an essential element is approximately $1 \mu\text{g kg day}^{-1}$ (CCME 2003). The health effects of Se are summarized in Table 2-8.

Table 2-8. Adverse health effects of selenium on humans and animals (CCME 2003).

	Humans and Animals	Animals
Adverse effects	Dizziness, fatigue, irritation, collection of fluid in the lungs, and severe bronchitis. Rashes, swelling, and pain upon contact with skin.	Reproductive and developmental effects; selenium sulphide is carcinogenic.

2.2.9 Health Effects Associated with Zinc

Zinc (Zn) is an essential nutrient required for proper growth, development, and function in mammals and birds (CCME 2003). Humans can handle a large zinc concentration, but too much zinc can still cause health problems (Lenntech 2005g). The health effects of Zn are summarized in Table 2-9.

Table 2-9. Adverse health effects of zinc on humans and animals.

	Information source	
	(CCME 2003)	Lenntech (2005g)
Adverse effects	Animals: loss of appetite, decreased water consumption and dehydration, increased mineral consumption, weakness, jaundice, diarrhea, and paralysis of the legs in birds.	Humans: stomach cramps, skin irritations, vomiting, nausea and anaemia; damage to the pancreas, arteriosclerosis and protein metabolism trouble; dangerous to unborn and newborn children.

2.2.10 Health Effects Associated with Cobalt

According to ATSDR (2004b), cobalt (Co) is essential to the body as a component of cyanocobalmin (vitamin B₁₂). The recommended dietary allowance of vitamin B₁₂ is $2.4 \mu\text{g d}^{-1}$, which contains $0.1 \mu\text{g Co}$ (ATSDR 2004b). However, excessive exposure to

cobalt may damage human health (ATSDR 2004b). The health effects of cobalt are summarized in Table 2-10.

Table 2-10. Adverse health effects of cobalt on humans and animals (ATSDR 2004b).

	Humans	Animals
Adverse effects	Respiratory effects (including decreased pulmonary function, asthma, interstitial lung disease, wheezing, and dyspnea); increase in erythrocyte numbers (polycythemia); allergic dermatitis; cobalt and cobalt compounds are possibly carcinogenic.	Respiratory tract hyperplasia, pulmonary fibrosis, and emphysema; increased tumor incidences.

2.2.11 Health Effects Associated with Molybdenum

No information about the health effects of Mo is provided in the Canadian Soil Quality Guidelines for the Protection of Environmental and Human Health (CCME 2003).

According to Lenntech (2005e), animal experiments indicated that molybdenum and its compounds are highly toxic. The adverse health effects of Mo on humans were observed in a Mo-Cu plant located in the Soviet Union. The information about the health effects of Mo is summarized in Table 2-11.

Table 2-11. Adverse health effects of molybdenum on humans and animals (Lenntech 2005e).

	Humans	Animals
Adverse effects	Gout among factory workers and inhabitants of Mo-rich areas (joint pains in the knees, hands, feet, articular deformities, erythema, and edema of the joint areas); liver dysfunction.	Fetal deformities.

2.3 Compost Environmental Protection Standards for Trace Metals

2.3.1 Canada-Wide and Provincial Trace Metal Concentration Limits

Canada-wide and provincial standards, regulations, and guidelines for trace metals in compost are in place to protect the environment and health of humans and animals. The

across-Canada organizations involved in setting the standards include the Canadian Food Inspection Agency (CFIA), which regulates compost for sale, the Bureau de normalisation du Québec (BNQ), which sets voluntary standards, and the Canadian Council of Ministers of the Environment (CCME), which encourages the harmonization of provincial standards. Provincial governments are also responsible for compost standards for the composts produced and applied in particular provinces.

British Columbia, Ontario and Quebec set their own provincial limits for trace metals in compost. The other provinces, Alberta (AB), Saskatchewan (SK), Manitoba (MB), Prince Edward Island (PE), Nova Scotia (NS), Newfoundland & Labrador (NF), and New Brunswick (NB), have adopted the CCME guidelines for compost quality (CCME 2005). The provincial and across-Canada maximum concentration limits for trace metals in compost are summarized in Table 2-12. The BNQ (2005) trace metal limits for types AA and A composts are the same as those for Quebec C1 category compost (Environment Quebec 2004). The BNQ types AA and A limits for trace metals are identical with those limits for CCME category A. The mercury limits of the various jurisdictions have a large variation, ranging from 0.15 mg kg^{-1} (for Ontario regular leaf and yard waste compost) to 15 mg kg^{-1} (for BC Class B compost). Ontario recently adopted the CCME category A values for trace metals for all composts except leaf and yard waste compost (Environment 2004). The CFIA does not classify compost. The CFIA compost limits for trace metals (CFIA 1997) have been adopted as the limits of CCME Category B and BNQ Type B composts.

Table 2-12. Summary of across Canada and provincial limits for trace metals in compost.

Trace Metal ^c (mg kg ⁻¹ , dw)	Ontario ^a		British Columbia ^c		Quebec ^e		AB, SK, MB, NB, NS, PE, NF	
	Regular	Controlled	Class A	Class B	C1	C2	ON ^b ; CCME A; BNQ AA & A	CCME B; BNQ B; CFIA
As	10	20	13	75	13	40	13	75
Cd	3	4	3	20	3	10	3	20
Co	25	25	34	150	34	150	34	150
Cr	50	50	100	1060	210	1060	210	1050 ^d
Cu	60	100	400	2200	400	1000	400	750 ^d
Hg	0.15	0.5	2	15	0.8	5	0.8	5
Mo	2	3	5	20	5	20	5	20
Ni	60	60	62	180	62	180	62	180
Pb	150	500	150	500	150	300	150	500
Se	2	2	2	14	2	14	2	14
Zn	500	500	500	1850	700	1850	700	1850

^a Ontario trace metal limits for leaf and yard waste compost (OME 1994).

^b Ontario trace metal limits for all compost except leaf and yard waste compost (Environment 2004). Compost that does not meet the limits is considered as waste but can still be land applied with a Certificates of Approval, which takes into account such things as separation distances and application rates (Guglietti 2005).

^c BC (2002).

^d For CFIA only. CFIA internal standards.

^e Environment Quebec (2004)

2.3.2 Cumulative Metal Additions to Soil Limits

In addition to regulating maximum acceptable concentrations of trace metals, end-use restrictions are also included. The CFIA has set acceptable limits for cumulative metal additions to soil in the CFIA Trade Memorandum T-4-93 (CFIA 1997) under the *Fertilizers Act and Regulations*. The CFIA maximum acceptable cumulative metal addition limits over the long term (45 years) are As 15, Cd 4, Co 30, Hg 1, Mo 4, Ni 36, Pb 100, Se 2.8, and Zn 370 kg ha⁻¹. The maximum acceptable cumulative metal additions to soil for Cu and Cr are not included in the Trade Memorandum, but the CFIA has

interim maximum acceptable cumulative metal addition standards for Cu and Cr, which are 150 and 210 kg ha⁻¹ respectively (Ring and Madey 2005). Currently, the CFIA interprets maximum annual loadings as 1/45 of these values. The CFIA established these loading rates by using the mean levels of trace metals in agricultural soils in Ontario and converting the difference in concentration between “mean” and “acceptable” soil levels to loading rates (Environment Quebec 2004).

2.4 Discussions on Trace Metal Limits

Among the three Canada-wide trace metal standards, only the CFIA Trade Memorandum T-4-93 (CFIA 1997) is mandatory. The BNQ standard (BNQ 2005) serves as a reference document for voluntary use. The CCME guidelines (CCME 2005) come into effect only if adopted by jurisdictions.

The CFIA (or CCME Category B or BNQ Type B) concentration limits for trace metals are not over restrictive. It is not very challenging for MSW and biosolids composters to meet these limits. A comparison between trace metal concentrations in some composts and the CFIA limits is provided in Table 2-13. All the trace metal concentrations in MSW and biosolids composts are much lower than the CFIA limits. These composts are safe in terms of the CFIA concentration limits. However, this does not mean that such composts can be applied without restrictions to land or in crop production in Canada. The CFIA Trade Memorandum T-4-93 requires composts to be applied in accordance with the maximum acceptable cumulative metal additions to soil.

Table 2-13. Comparison of compost trace metal concentrations to CFIA limits.

Trace Metal (mg kg ⁻¹ , dw)	CFIA Limits	Mixed MSW Compost (Edmonton) ^a	Mixed MSW Compost (U.S.) ^b	Composted Biosolids (U.S.) ^b	Separated MSW Compost (EU) ^b
As	75	7.9	2.6	5.0	NA
Cd	20	3.6	2.9	4.5	1.1
Co	150	5.5	NA	NA	NA
Cr	1050	98.8	34	52.6	29.4
Cu	750	240.3	162	380	57
Hg	5	1.0	1.2	2.0	0.9
Mo	20	4.3	NA	12.9	NA
Ni	180	54.2	28	28.1	19.9
Pb	500	163.9	221	72.6	112
Se	14	0.9	NA	3.9	NA
Zn	1850	635.9	469	821	281

^a Average compost concentration (City of Edmonton 2002, 2003, 2004).

^b Moss et al. (2002).

NA – Not available

The maximum acceptable cumulative metal additions will limit the application of total compost to the same soil over time (Zhang et al. 1998). The levels of the trace metals Zn, Pb, Cu, Cd, Ni, and Cr will determine the total amount of Edmonton compost that can be applied to a body of soil (Zhang et al. 1998). Based on the maximum acceptable cumulative metal additions to soil and the average concentrations of Edmonton compost, the maximum compost addition to soil was calculated to be about 13 dry tonnes ha⁻¹ per year. Zinc and lead are the most limiting trace metals for Edmonton compost.

2.5 Summary and Conclusions

- Accumulation of trace metals in large quantities in soils over the long term may cause harmful effects on human health and the environment although some of the trace metals are essential or beneficial to plants and animals.

- Trace metals are regulated by compost environmental protection standards in Canada to protect humans and the environment. Both compost concentration limits for trace metals and maximum acceptable cumulative metal additions to soil have been established in compost standards. The trace metal concentration limits of CCME, BNQ, and CFIA are given in Table 2-12. The CFIA maximum acceptable cumulative metal addition limits are given in Section 2.3.2.
- British Columbia, Ontario and Quebec have set their own provincial compost limits for trace metals. The other provinces, Alberta (AB), Saskatchewan (SK), Manitoba (MB), Prince Edward Island (PE), Nova Scotia (NS), Newfoundland & Labrador (NF), and New Brunswick (NB), have adopted CCME guidelines for compost quality.

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Chapter 3 Priority Trace Metals in Mixed Municipal Solid Waste Compost Systems

3.1 Introduction

The benefits associated with land application of compost are obvious, e.g., the return of nutrients to soil and the improvement of the physical conditions of soil. However, a potential risk (the accumulation of trace metals in soils) exists in the use of compost. A high content of trace metals in compost can make the compost unsuitable for application on agricultural land (de Bertoldi 1993). Compost environmental protection standards for trace metals are in place in Canada to protect the environment and human health. There are three Canada-wide standard-setting organizations, the CFIA, BNQ, and CCME. A brief introduction to these organizations and their standards for compost is given in this section.

All composts sold in or imported into Canada must comply with the requirements of the *Canadian Fertilizers Act*. The CFIA does not classify compost. The concentrations of trace metals in compost and compost application rate are subject to Trade Memorandum T-4-93: Standards for Metals in Fertilizers and Supplements (CFIA 1997). The CFIA trace metal limits are given in Section 2.3, Table 2-12.

The BNQ has a voluntary standard for trace metals. This standard serves only as a reference document for voluntary conformity assessment activities of compost producers

(BNQ 2005). The BNQ standard can become mandatory where legislation or regulations stipulate its use. The BNQ trace metal limits are provided in Table 2-12.

The CCME is an intergovernmental forum that has been utilized by the provinces and territories to decide regulations for compost products. The CCME established Guidelines for Compost Quality in 1996 and revised these guidelines in 2005 (CCME 2005). The CCME trace metal limits are given in Table 2-12. It is the responsibility of each province and territory to decide whether or not the CCME guideline is adopted within their own jurisdictions. Except for British Columbia, Ontario and Quebec, which have their own compost regulations and guidelines, the other seven provinces in Canada including Alberta have adopted the CCME guidelines. The CCME (2005) recommends that CCME Category A composts can be used in any application, such as in agriculture, residential gardens, horticultural operations, the nursery industry, and other businesses. CCME Category B composts can be used only in restricted applications. However, the phrase "restricted application" is not specified in the CCME guidelines. Therefore, it is left to the provinces to determine appropriate applications for CCME Category B composts.

In Alberta, CCME Category B composts can be applied on cropland with approval from the CFIA. The City of Edmonton acquired its Class 1 Composting Facility approval (No. 2044-00-02) in November, 2002 from Alberta Environment. The approval requires that "compost for sale or use within the province of Alberta shall be classified according to the current Guidelines for Compost Quality, Canadian Council of Ministers of the Environment, as amended, or as otherwise authorized in writing by the Director." The

approval also requires that "unless authorized in writing by the Director, the approval holder shall not dispose of compost material in Alberta if it fails to meet the criteria for either Category A or B compost (CCME Guidelines) or Registration under the *Fertilizer Act*." Edmonton compost meets the trace metal criteria for CCME Category B compost. The compost is allowed to be applied up to 10 dry tonnes per hectare annually on cropland as required by the CFIA in the approved label for City of Edmonton Compost (1-0.7-0.2).

Whether or not Edmonton compost meets the CCME Category A requirements for trace metals is not a significant issue in light of the agricultural use of Edmonton compost. However, the annual application rate of 10 dry tonnes (17 wet tonnes at 40% moisture content) per hectare is somewhat restrictive to a large scale composter like the Edmonton Composting Facility (ECF). The low application rate may have negative impacts on compost marketing and the end use of compost.

The low application rate is directly correlated to a high cropland demand. For example, about 68,000 wet tonnes (40,800 dry tonnes at 40% of moisture content) of compost was produced by the ECF in 2002 (City of Edmonton 2003a). This would require for disposal about 4,080 hectares of cropland at the application rate of 10 dry tonnes per hectare. If the application rate was increased to 15 dry tonnes per hectare, only 2,720 hectares of cropland would be required.

The low application rate can inhibit farmers from sufficiently benefiting from the amending effects of compost. In agricultural production, a compost application rate of much higher than 17 wet tonnes (as required by the CFIA) is needed to realize the agronomic value of compost. It was reported that more than 30 wet tonnes per hectare of MSW compost is needed to noticeably increase organic matter in soil and improve the physical properties of soil (Kirchhoff et al. 2002). In amending poor soils with a low organic content, a typical compost application rate of about 300 wet tonnes per hectare is required (Darlington 2006).

In addition, increased costs for land application may result from a lower application rate. For example, equipment costs for applying and incorporating compost will be higher as more time will be required to apply the same amount of compost.

Therefore, reducing the levels of trace metals in compost and increasing the application rate of compost are important to MSW composters. Doing so can make the marketing of compost easier and help realize the agronomic value of compost. An important issue when looking at reducing trace metal levels of compost is whether the eleven trace metals in compost are of equal importance. This study was carried out to identify priority trace metals by comparing the trace metal concentrations of Edmonton MSW compost to the CCME trace metal limits.

3.2 Compost Trace Metal Concentration Data

The trace metal concentration data for MSW composts found in the literature mainly involves seven trace metals – Cd, Cr, Cu, Hg, Ni, Pb, and Zn. Little concentration information for the other four trace metals (As, Co, Mo and Se) is available from the published literature. The MSW compost metal data from the Edmonton Composting Facility (ECF) covers all of the eleven trace metals regulated in Canada. The trace metal concentration data from the ECF were analyzed in this study.

3.2.1 Edmonton Composting Facility (ECF) Material Flow Diagram

The ECF material flow diagram is provided in Figure 3-1 (City of Edmonton 2005). According to the 2001 Annual Report (City of Edmonton 2002), the average material retention times (MRT) for each process are 0.6 days in a mixing drum and 17.5 days in composting. Theoretically, after an average of 18.1 days, the composted material is moved from the aeration bays to the cure site where the compost is cured for 7-8 months.

3.2.2 Analysis of Trace Metal Concentration

Each trace metal exists in different forms in compost: exchangeable, carbonate bound or acid extractable, iron (Fe) and manganese (Mn) oxides bound or reducible, organic matter bound or oxidisable, and residual. Different forms of a metal exhibit different leachabilities and availabilities to living organisms. There are normally three types of trace metal analyses, (1) total metals, (2) recoverable (environmentally available) metals, and (3) leachable (bioavailable) metals (Environment Canada 2005).

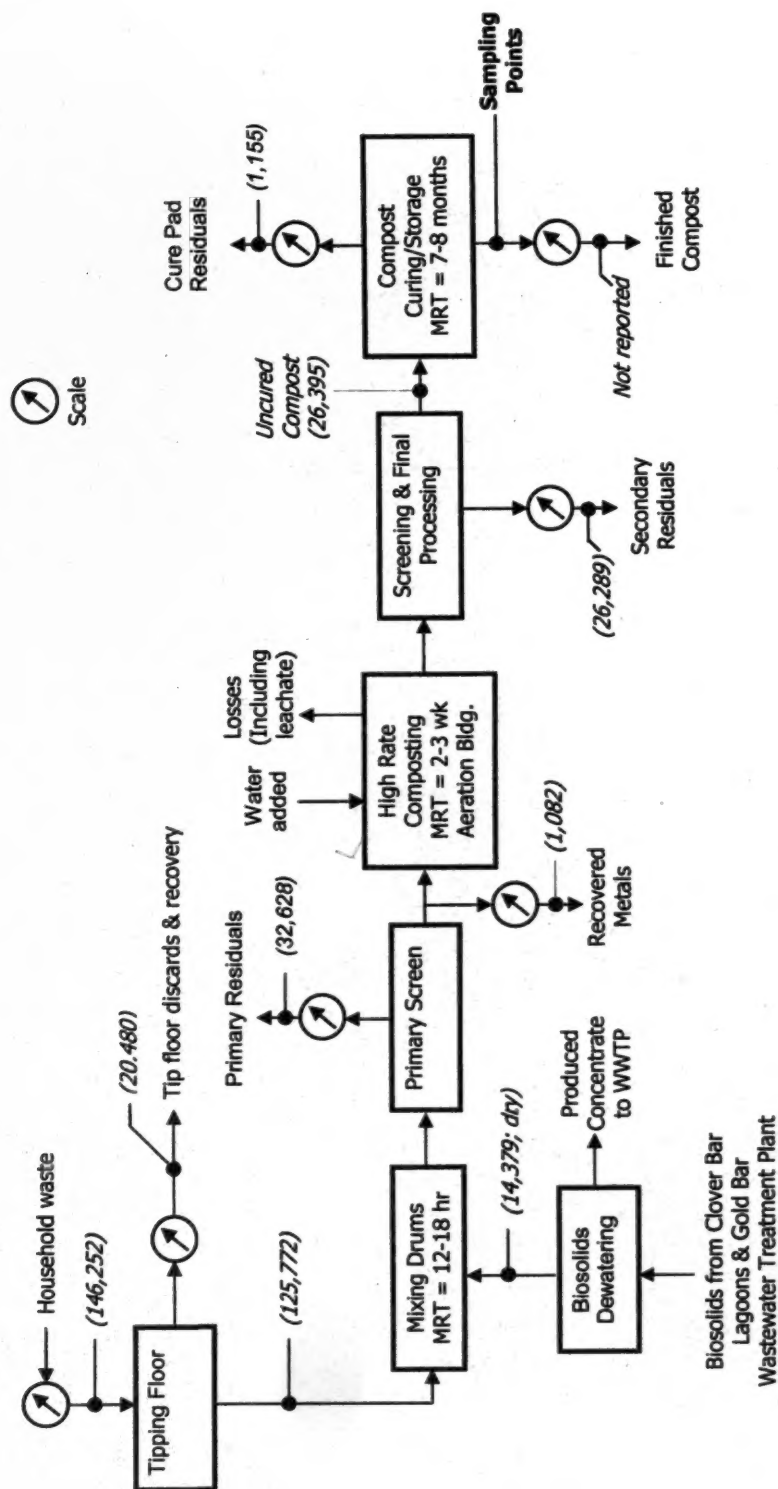


Figure 3-1. The ECF material flow diagram. Numbers given in brackets () represent the wet tonnages (except biosolids in dry tonnes) for 2004 (City of Edmonton 2005).

(1) **Total Metals:** According to Environment Canada (2005), total metals analysis requires the complete destruction of a sample in order to release all forms of metal. These include metals adsorbed on the sample particles, metals in the form of insoluble salts and organic complexes, and metals in a mineral phase. Decomposition of the sample is achieved by treating it with a mixture of strong acids. Hydrofluoric acid (HF) is required to break up the silica matrix and to liberate all entrapped metals.

(2) **Recoverable (Environmentally Available) Metals:** To extract recoverable metals, strong acid digestion without hydrofluoric acid is used (e.g., aqua regia). Such procedures recover metals adsorbed on the sample particles and metals in the form of insoluble salts and organic complexes, while metals trapped within the silicate matrix are not extracted (Environment Canada 2005).

With respect to the CCME, CFIA and BNQ standards, metal standard limits refer to recoverable metal contents. The CCME and BNQ recommend that Method 3050B - Acid Digestion of Sediments, Sludges, and Soils (USEPA 1996) and Method 3051 - Microwave Assisted Acid Digestion of Sediments, Sludges, Soils, and Oils (USEPA 1994) be used for the analysis of trace metals in compost (BNQ 2005). Method 3050B is a very strong acid digestion technique. Almost all elements that could become environmentally available will be dissolved using this method. Method 3051 is an alternative to Method 3050B. All trace metal concentrations reported in this chapter are determined using Method 3050B.

(3) Leachable (Bioavailable) Metals: Leachable metal levels are determined by a room-temperature strong acid digestion method. This method is different from that used for determining recoverable metals, in which high-temperature strong acid digestion is used.

3.2.3 Trace Metal Concentrations of Edmonton MSW Compost

Data from a real world operation – the Edmonton Composting Facility (ECF) – were used in this study. Specifically, trace metal concentration data from twenty cured compost samples were analyzed. Trace metal data were found in the City of Edmonton's annual reports for the years 2002 (for ten samples), 2003 (for seven samples), and 2004 (for three samples) (City of Edmonton 2003b, 2004, 2005). The compost samples were analyzed by the Norwest Labs or Enviro-Test Laboratories. Both labs have their quality assurance programs guiding and monitoring the integrity of samples and results from the time samples arrive at the labs until the final report is issued. The samples were analyzed in accordance with the CCME guidelines.

Probabilities of Compliance with CCME Metal Limits

Cumulative frequency distribution plots were developed based on the trace metal data from 20 samples (Appendix A, Figures A-1 to A-11). Means, medians, and trace metal limits for CCME Category A and B composts are given in the plots. A summary of the cumulative frequency distribution plots is provided in Table 3-1.

Concentrations of all the eleven trace metal for all samples were much lower than the CCME Category B trace metal limits. The ECF compost is 100% compliant with the

CCME Category B limits. However, exceedances of CCME Category A limits exist. The probability of compliance with the CCME Category A limit for each metal was determined by counting the exceedances of the trace metal limit from the plots.

Table 3-1. Probabilities of compliance with CCME Category A limits.

Trace Metal	Mean, mg kg^{-1}	%RSD	Median, mg kg^{-1}	CCME A limit, mg kg^{-1}	Compliance probability
As	7.9	62.8	6.6	13	85%
Cd	3.6	33.6	3.4	3	25%
Cr	98.8	58.2	81.9	210	95%
Co	5.5	18.6	5.3	34	100%
Cu	240	38.3	221	400	95%
Pb	164	32.6	162	150	40%
Hg	1.0	40.0	0.8	0.8	50%
Mo	4.3	27.9	4.4	5	90%
Ni	54.2	23.5	54.5	62	85%
Se	0.9	85.0	0.7	2	90%
Zn	636	25.2	700	700	50%

Note: All eleven of the trace metal concentrations for all samples are compliant with CCME Category B limits.

For example, ten out of 20 samples exceeded the CCME Category A limit for Hg (Figure A-7), and thus the compliance probability for Hg was 50%. Similarly, the other compliance probabilities were determined, as summarized in Table 3-1. The probabilities of compliance with CCME Category A trace metal limits range from 25% to 100%.

It has been noticed from the plots that the distributions of concentrations of As, Cd, Cr, Co, Cu, Hg, and Se are not normal (they are positively skewed). The means of the data sets are higher than the medians. For example, the median of the Hg data is 0.8 mg kg^{-1} (probability (P) = 50%). The mean of the data set is 1.0 mg kg^{-1} , higher than the median (Table 3-1).

Temporal Trend of Trace Metal Concentrations

Among the 20 samples, there were only nine whose production dates were indicated in the annual reports. The production dates were between May 2001 and December 2002. Based on the available information on production dates, temporal-trend plots of concentration versus production dates were developed to reveal any peculiarities in the change of trace metal content. The temporal trend charts for 11 trace metals are presented in Appendix B, Figures B-1 to B-11. The features of the temporal trend plots are summarized in Table 3-2. The temporal trend plots do not show a strong trend in general. More data are needed to identify any obvious trends.

Table 3-2. Temporal features of trace metal concentrations of Edmonton MSW compost.

Trace Metal	Temporal Trend Features
As	Fluctuating without obvious trends of increases or decreases; a sharp increase, 24.1 mg kg ⁻¹ , appeared in September 2001; this value was about three times as large as the average.
Cd	Fluctuating around 3.3 mg kg ⁻¹ . More data needed to verify if a decreasing trend exists.
Cr	The average concentration of Cr is lower in 2002 than in 2001.
Co	The average concentration of Co is lower in 2002 than in 2001.
Cu	No obvious increasing or decreasing trend; a sharp increase, 553 mg kg ⁻¹ , appeared in September 2001; this value is about two times as large as the average.
Pb	No obvious increasing or decreasing trend.
Hg	No obvious increasing or decreasing trend.
Mo	The average concentration is higher in 2002 than in 2001.
Ni	No obvious increasing trend.
Se	The average concentration is lower in 2002 than in 2001.
Zn	The average concentration is higher in 2002 than in 2001.

3.3 Method for Identifying Priority Trace Metals

A compost either passes or fails the requirements of the CCME guideline. Each trace metal limit for the CCME Category A compost must be met in order for compost to be

classified as Category A. Any exceedance of the trace metal criteria can result in a lower classification. Thus, the number of exceedances of CCME Category A limits is an important factor to be considered in identifying priority trace metals. The percentage number of exceedances (the number of exceedances / total number of samples $\times$ 100%) is actually the complement of compliance probability. For example, 15 of the 20 samples exceeded the CCME Category A limit for Cd. The percentage number of exceedances is then 75% ($15 / 20 \times 100\%$), which is the complement of the compliance probability of 25% ($100\% - 75\%$) shown in Table 3-1.

In addition to number of exceedances, the level of exceedances of the CCME Category A limits cannot be ignored because a higher level of exceedances may lead to greater environmental impacts and may require more efforts in reducing trace metal content than a lower one. Therefore, priority trace metals were identified based on each of the three criteria respectively – the number of exceedances (or compliance probability), level of exceedances, and a combination of number and level of exceedances.

Through comparison of concentrations of 20 samples for each trace metal to the corresponding CCME Category A limit, the number of times for which the trace metal limit was exceeded could be determined. Based on the numbers of exceedances, priority trace metals were then identified. The trace metal that exceeded the CCME limit most frequently was of the highest priority. The trace metal was not of priority if the number of exceedances of the trace metal limit was zero.

The level of exceedances of each metal limit was obtained by subtracting the guideline limit from the metal concentrations. Then the percentage level of exceedances was calculated. The priority trace metal sequence based on the level of exceedances was determined according to the average percentage level of exceedances of each metal limit.

The priority trace metal sequence based on both number and level of exceedances was determined by using a compounded score. The compounded score was determined using the formula $(A)^2 \times B$. Parameter "A" is related to number of exceedances, and "B" is related to level of exceedances. This formula assumes that consistent exceedance is worse than a one-time high-level exceedance. The rationale for this is that the occurrence of exceedance of the guideline limits is determinant for compost classification, regardless of the level of exceedances. Thus, parameter A is in second order in the formula. To illustrate how the compounded score was calculated, an example is given as follows.

One of the 20 samples exceeded the CCME A limit for Cr; in other words, 5% of the total samples exceeded the limit. The level of exceedances was 29.5% of the CCME A limit. Thus, "A" equals to 1.05, and "B" is 1.295. The compounded score $(A)^2 \times B$ equals to $(1.05)^2 \times 1.295 = 1.43$.

3.4 Results and Discussion

Twenty cured compost samples, representing composts produced in 2002, 2003, and 2004, were used to identify priority trace metals. In comparison to the CCME Category A trace metal limits, the priority trace metals for Edmonton MSW compost were

determined based on the number of guideline exceedances, level of guideline exceedances, and compounded score respectively.

3.4.1 Priority Ranking of Trace Metals based on Number of Exceedances

The numbers of exceedances for 11 trace metals and priority ranking of the metals are presented in Table 3-3. Among 20 samples, 15 samples exceeded the Cd limit; 12 samples exceeded the Pb limit; ten samples exceeded the Hg and Zn limit; three samples exceeded the As and Ni limits; two samples exceeded the Mo and Se limits; and one sample exceeded the Cr limit. No samples exceeded the Co limit. Thus, Co is not of priority. The priority sequence of the other ten trace metals is:

$Cd > Pb > Hg \text{ \& } Zn > Ni \text{ \& } As > Mo \text{ \& } Se > Cu \text{ \& } Cr$

Largest $\rightarrow$ Smallest number of exceedances.

Table 3-3. Priority ranking of trace metals based on number of exceedances.

Trace Metals	Number of Exceedances		Priority Ranking ²
	Number	% ¹	
As	3	15.0	5
Cd	15	75.0	1
Cr	1	5.0	9
Co	0	0	N ³
Cu	1	5.0	9
Pb	12	60.0	2
Hg	10	50.0	3
Mo	2	10.0	7
Ni	3	15.0	5
Se	2	10.0	7
Zn	10	50.0	3

Note: Number of exceedances was determined in comparison with CCME Category A limits for trace metals. There were 20 samples in total.

¹ Percentage (%) = number of exceedances / number of samples $\times$ 100.

² Number "1" indicates the number of exceedances for the metal is the highest. "9" indicates the number of exceedances for the metal is the lowest.

³ N - No exceedances.

3.4.2 Priority Ranking of Trace Metals based on Level of Exceedances

The levels of exceedances for 11 trace metals and priority ranking of the metals are presented in Table 3-4. All samples met the CCME Category A limit for Co; thus, Co is not of priority. The levels of exceedances for the other metals range from 5.0% to 63.5%.

Based on the level of exceedances, the priority sequence of the ten trace metals is:

Hg > As > Cu > Cd > Pb > Cr > Mo > Ni > Zn > Se

Highest → lowest level of exceedances.

Table 3-4. Priority ranking of trace metals based on level of exceedances.

Trace Metals	Level of Exceedances		Priority Ranking ³
	Average ¹ , mg kg ⁻¹	% ²	
As	5.2	40.3	2
Cd	0.93	31.1	4
Cr	62.0	29.5	6
Co	N ⁴	N ⁴	N ⁴
Cu	153	38.3	3
Pb	45.0	30.0	5
Hg	0.51	63.5	1
Mo	1.2	24.4	7
Ni	12.0	19.4	8
Se	0.1	5.0	10
Zn	61.3	8.8	9

Note: Level of exceedances was determined in comparison with CCME Category A Limits for trace metals. There were 20 samples in total.

$$^1 \text{ Average level of exceedances for each metal} = \frac{\sum_{i=1}^n (\text{concentration} - \text{limit})}{n}$$

²Percentage (%) = average level of exceedances / guideline limit × 100.

³Number "1" indicates the level of exceedances (%) for the metal is the highest. "10" indicates the level of exceedances (%) for the metal is the lowest.

⁴N - No exceedances.

3.4.3 Priority Ranking of Trace Metals based on Number and Level of Exceedances (Compounded Score)

The compounded scores and priority ranking of trace metals are presented in Table 3-5.

The calculation of the compounded scores $(A)^2 \times B$ was based on both the number and level of exceedances, which is given in Section 3.3. The compounded scores range from 1.27 (for Se) to 4.01 (for Cd). Thus, Cd is of the highest priority, and Se is of the lowest priority. The priority sequence of trace metals is:

Cd > Hg > Pb > Zn > As > Ni > Cu > Mo > Cr > Se

Largest → Smallest compounded score.

Table 3-5. Priority ranking of trace metals based on both number and level of exceedances (compounded score).

Trace Metals	Number of Exceedances, %	A	Level of Exceedances, %	B	Compounded Score = $(A)^2 \times B$	Priority Ranking ¹
As	15.0	1.15	40.3	1.403	1.86	5
Cd	75.0	1.75	31.1	1.311	4.01	1
Cr	5.0	1.05	29.5	1.295	1.43	9
Co	0	N ²	N ²	N ²	N ²	N ²
Cu	5.0	1.05	38.3	1.383	1.52	7
Pb	60.0	1.6	30.0	1.300	3.33	3
Hg	50.0	1.5	63.5	1.635	3.68	2
Mo	10.0	1.1	24.4	1.244	1.51	8
Ni	15.0	1.15	19.4	1.194	1.58	6
Se	10.0	1.1	5.0	1.050	1.27	10
Zn	50.0	1.5	8.8	1.088	2.45	4

Note: "A" is related to number of exceedances, and "B" is related to level of exceedances.

¹ Priority ranking based on compounded score. Number "1" indicates the highest priority; "10" indicates the lowest priority.

² N - No exceedances.

3.4.4 Comparison of Priority Rankings of Trace Metals

The three priority rankings based on the number of exceedances, level of exceedances, and compounded score are different. A comparison of the three rankings is given in

Figure 3-2. The priority rankings of trace metals based on the level of exceedances (level-based) are very different from those based on the number of exceedances (number-based) and compounded scores. Arsenic and Cu are the second and third metals in the level-based ranking, while As and Cu are the sixth and ninth in the number-based ranking. In the compounded-score ranking, they are the fifth and seventh respectively. Cadmium is the first in both number-based and compounded-score rankings, while the number one metal in the level-based ranking is Hg. Zinc is among the first four metals in number-based and compounded-score rankings, while Zn is the ninth metal in the level-based ranking.

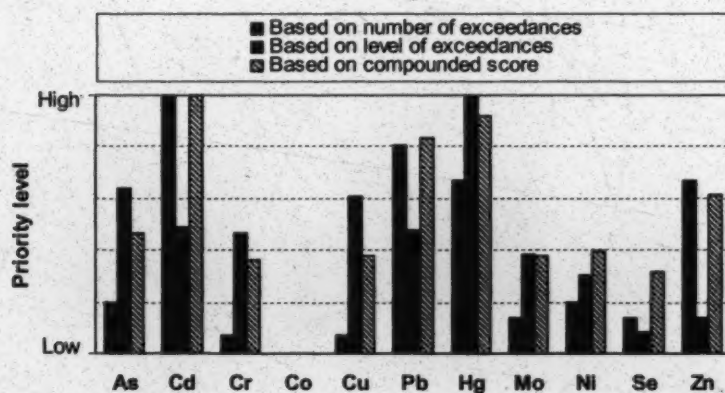


Figure 3-2. Comparison of priority rankings of trace metals based on different factors.

The number-based ranking is similar to the compounded-score ranking. The first four metals of high priority are the same in the two rankings, i.e. Cd, Hg, Pb, and Zn. This is due to the fact that "number of exceedances" carries more weight in the compounded score ranking. It has been noticed that the three trace metals (Cd, Pb, and Hg) of high

priority are the metals of no known value to either plants or animals listed in the CCME Guidelines for Compost (CCME 2005).

It may be appropriate to use the priority ranking of trace metals based on the compounded score in trace metal contaminant reduction programs because both the number and level of exceedances are considered in the compounded-score ranking.

3.5 Conclusions

- MSW compost trace metal data from the Edmonton Composting Facility (ECF) are the most up-to-date. The data cover all the eleven trace metals regulated in Canada. The ECF is an excellent case facility for mixed MSW composting.
- The trace metal concentrations in Edmonton compost are much lower than the CCME Category B limits for trace metals. However, exceedances of the CCME Category A limits exist. The probabilities of compliance with CCME Category A trace metal limits range from 25% to 100%.
- Based on the number and level of exceedances (compounded score), priority trace metals are identified. The priority sequence of trace metals is: Cd > Hg > Pb > Zn > As > Ni > Cu > Mo > Cr > Se. It is recommended that this priority ranking be used in trace metal contaminant reduction programs.

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Chapter 4 Trace Metal Sources in Mixed Municipal Solid Waste Compost Systems ¹

4.1 Introduction

The knowledge of the sources of trace metals in MSW composting feedstocks is important in designing trace metal reduction processes and optimizing centralized separation technologies. Any trace metal reduction program begins with information about specific metal sources. Identification of trace metal sources is critical for effective separation of metal contaminants from composted materials (Richard et al. 1993).

However, identification of trace metal sources can be very complicated. First of all, trace metals are widely used in industrialized societies. Trace metals are used in hundreds of thousands of consumer goods and products. Some of these products will end up in the MSW stream. Second, studies of waste stream characterization rarely include trace metal analysis. Although some studies have provided analysis results of trace metal content, most of these studies gave only the metal content for very broad waste categories (Richard et al. 1993), offering little information about specific trace metal sources.

The study described in this chapter was carried out to identify the specific sources of trace metals in composting feedstocks by reviewing the literature on the manufacturing of consumer products and waste characterization studies. The results indicated that noncompostables could contribute to more than 86% of the total content of As, Cd, Cr, Cu, Pb, Hg, Ni, and Zn in MSW. MSW components such as batteries, electrical and

¹ *Some content of this chapter has been submitted for publication. Proceedings of 15th Composting Council of Canada Conference. October 12-14, 2005, Lake Louise, Alberta.*

electronic products, scrap metals, treated wood, textiles, rubber, and leather could be the sources of trace metals. Biosolids can be a significant source of Cd, Co, Mo, Se, and Cr in MSW/biosolids co-composting.

4.2 Trace Metal Consumption and Metal Flow in a Community

4.2.1 Trace Metal Consumption

The trace metals Cd, Co, Pb, Hg, Zn, Ni, As, Mo, Se, Cu, and Cr are widely used in consumer products and consumable goods. The data for world metal production and Canadian reported metal use are provided in Tables 4-1 and 4-2. Canadian reported metal uses for As (for 1998-2003) and Cr (for 1999-2003) are confidential and thus are not provided. The use of metal is heavily concentrated in industrialized countries (EMCBC 2005). For example, Canadians comprised 0.5% of the world's population in 1995; however, they consumed about 2% of the global nickel and zinc production of that year (EMCBC 2005).

Post-consumer products and consumable goods, which may contain trace metals, include barbeque starters, can openers, toys, weigh scales, tin cans, wires, twist ties, batteries, glass, lamps, lead capsules, plastics, etc. These metal-containing products may have an impact on the trace metal content of MSW compost.

Table 4-1. World metal production for 1998-2004 (thousands of tonnes). Mine production for: Cr, Cu, Hg, Mo. Other data are for refinery production or are not specified in the literature.

Year	1998	1999	2000	2001	2002	2003	2004
As ¹	30.5	31.6	29.4	26.5	26.5	NA	NA
Cd ²	19.2	19.6	19.4	17.9	16.4	NA	NA
Co ³	35.3	31.6	37.2	45.8	47.6	48.4	46.9
Cr ⁴	12700	12800	NA	12100	13000	15500	17000
Cu ⁵	12100	12800	13200	13700	13600	13600	14500
Hg ⁶	1.92	1.66	1.38	1.79	2.02	1.53	1.75
Mo ⁷	135	129	134	133	121	125	139
Ni ⁸	1180	1024	1082	1224	1229	NA	NA
Pb ⁹	3100	2966	3046	2998	2830	3108	NA
Se ¹⁰	1.47	1.41	1.46	1.46	1.46	1.43	1.50
Zn ¹¹	7570	8369	8981	9227	9712	9860	NA

NA - Not available.

¹ Buckingham and Brooks (2004). U.S. Geological Survey (GS).

² NRC (2003a) Canadian Minerals Yearbook, 2003.

³ Shedd (2005). U.S. Geological Survey (GS).

⁴ Papp (2005) U.S. Geological Survey (GS).

⁵ Edelstein (2005). U.S. Geological Survey (GS).

⁶ For data 1998-2002 (commodity): NRC (2005). Other data (mine production): Brooks (2005), USGS.

⁷ Index Mundi (2005).

⁸ McCutcheon (2002). NRC.

⁹ NRC (2003a). Canadian Minerals Yearbook, 2003.

¹⁰ George (2005) USGS.

¹¹ NRC (2003b). Canadian Minerals Yearbook, 2003.

Table 4-2. Canadian reported metal use (tonnes) for 1998-2003 (NRC 2005). Unless otherwise stated, use refers to reported use of refined metals or nonmetallic minerals by users.

Year	1998	1999	2000	2001	2002	2003
As	x	x	x	x	x	x
Cd	117	139	172	213	209	210
Cr	17000	x	x	x	x	x
Co	146	130	126	94.3	92.0	88.4
Cu ¹	246000	266000	272000	265000	274000	257000
Pb ²	87500	92600	81400	56900	66600	68400
Hg	2.80	x	x	5.61	2.13	4.87
Mo	2570	3180	2910	2450	2660	2240
Ni ³	19800	22500	25000	17700	19000	13000
Se	9.78	12.4	8.75	23.1	19.1	10.8
Zn	138000	143000	148000	145000	150000	146000

x - confidential

¹ Use defined as domestic shipments of refined copper as well as imports of refined copper

² Use of primary and recycled metal

³ Use of metallic nickel, all forms (refined metal, nickel in ferronickel, oxides and salts, and other forms of nickel including nickel in purchased scrap)

4.2.2 Metal Flow in a Community

The metal flow in a typical community is illustrated in Figure 4-1. The metal flow involves not only metals in raw materials or metal products but also metal-containing commodities and their packaging. In addition, the import and export of metal-containing goods and commodities and the recycling of metal-containing materials and products are involved. Thus, it is quite challenging to quantify the metal flow in a community.

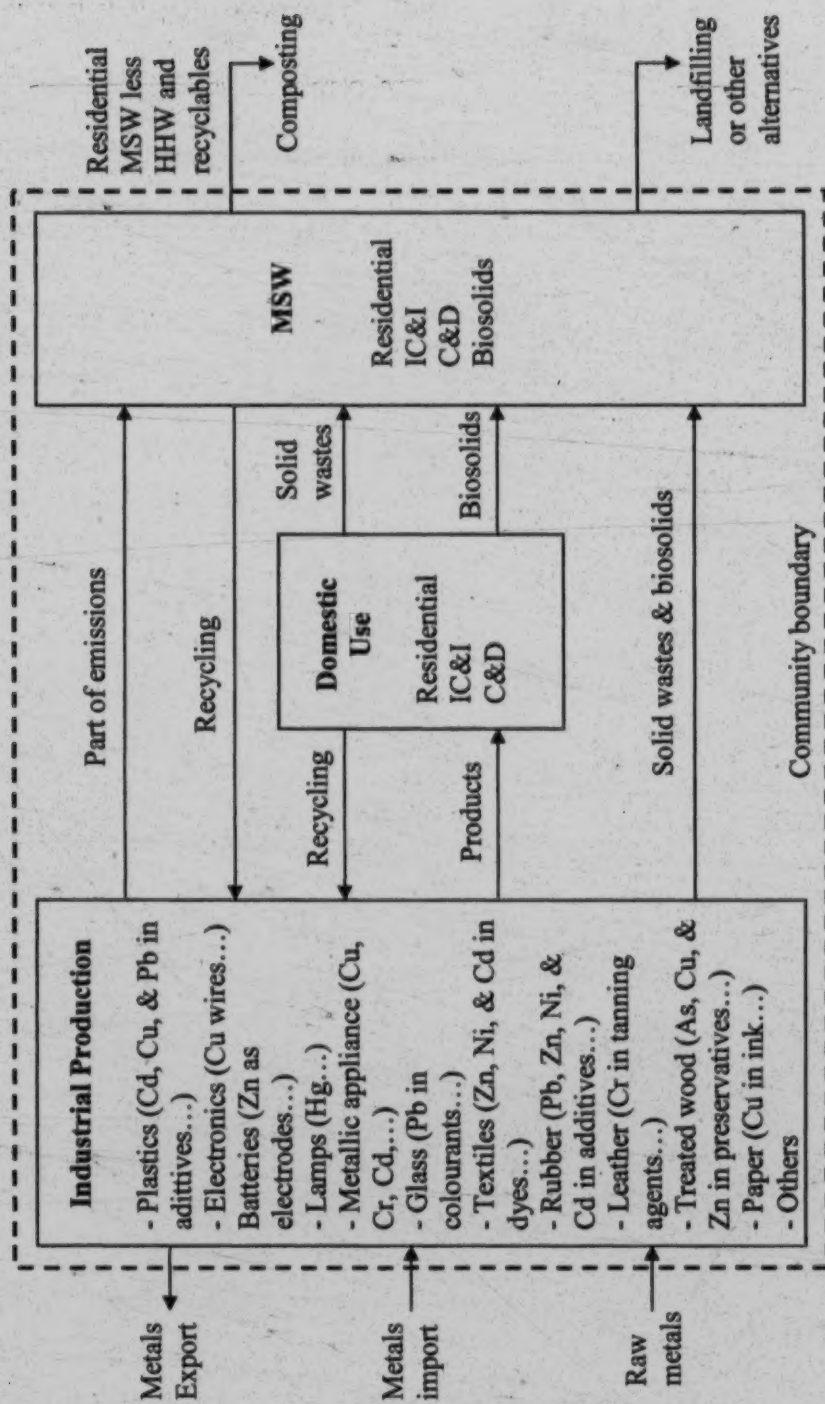


Figure 4-1. Metal material flow diagram for a typical community (Composting feedstock may contain waste components such as food, paper, cardboard, textiles, rubber, leather, residential yard waste, wood, glass, metal (wire, etc.), dust, batteries, remaining HHW and electronics, and other wastes generated in daily life).

4.3 Method for Identifying Sources of Trace Metals

There are basically two fundamental methods to characterize solid waste (Bailie et al. 1999). One is the material flows method in which data on the manufacture and sale of products are collected and analyzed. The second method involves a direct field study of solid waste. The advantages and disadvantages of the two methods are summarized in Table 4-3. One of the major drawbacks of the direct field study method is that too many resources (money, manpower and time) are required. It is extremely expensive to characterize trace metal concentrations in waste components. In comparison to the direct field study method, the material flows method is superior in terms of resources. In spite of its drawbacks, such as the difficulty of obtaining complete production data, as listed in Table 4-3, the material flows method is attractive because it is based on existing data and is relatively inexpensive.

An approach, involving a thorough review of the literature on manufacturing and waste characterization studies, was used in this study to identify the potential sources of metals. This approach was somewhat similar to the material flows method (based on existing literature), but the attempt to track material inputs and outputs associated with residential communities was not made because it is too difficult to acquire information about the quantities of metal-containing products sold, discarded post-consumer products, waste materials recycled, and imported and exported commodities.

Table 4-3. Advantages and disadvantages of two basic MSW characterization methods.

Method	Advantages	Disadvantages
Material flows	Based on existing data ² ; Measuring waste stream instead of samples of MSW ² ; Relatively inexpensive ² ;	Difficult to obtain complete production data ² ; Not account for addition of nonmanufactured materials to MSW, including soil, dust, etc. ² Lack of consistency of material categories in material flows studies with those targeted for recycling; ²
Direct field study	Site specific ¹ ; Suitable for local MSW ¹ ;	Expensive (a budget of \$100,000 typically required) ² ; Skilled and experienced team required ² ; Long period required to account for seasonal variation ¹ ;

¹ Martin et al. (1995)

² Bailie et al. (1999)

This study was completed to characterize the trace metal concentrations of waste categories and to find the nuggets of trace metals that could be separated from compost systems. Through a study of the manufacturing literature on consumer products, trace metals used in making the products were identified. Manufacturing literature also revealed the metal levels in some products, e.g., the amount of mercury in lamps. Waste characterization studies revealed the contribution of each broad waste category to the metal content of MSW and the metal concentrations of some waste components. Trace metal sources were identified based on information from both manufacturing and waste characterization literature.

4.4 Results and Discussion

The results of the literature review of noncompostable MSW components are presented in this section. Compostable MSW fractions, except for paper, are not included because studies indicated that compostables were not likely to be the sources of trace metals in the

MSW stream (Rugg and Hanna 1992). Table 4-4 gives the trace metal contents in MSW compostables and noncompostables (Rugg and Hanna 1992). Trace metal concentrations in noncompostables are much higher than in compostables. Basic organic materials to be composted, i.e., bread, vegetables, fruit, and garden waste, were relatively free of heavy metals (Van Roosmalen et al. 1987). The noncompostable fraction of MSW contributes significantly to the metal content in MSW.

Table 4-4. Metal concentrations (mg kg^{-1}) in compostable and noncompostable fractions of MSW in Cape May, U.S. (Rugg and Hanna 1992).

Waste type	As	Cd	Cr	Cu	Pb	Hg	Ni	Zn
Compostable	0.8	0.2	5.9	66	31	0.7	4.7	116
Noncompostable	6.2	10	830	1160	301	12	71	1146
Overall	3.3	4.5	377	534	152	5.8	34	579

Note: 1. Compostable: includes newspaper, corrugated cardboard, kraft paper, high-grade paper, magazines, other paper, yard waste, food waste, disposable diapers, fines, and other organics. Other organics means carbon-containing wastes not otherwise categorized, including cigarette butts, hair, wax, linoleum, dryer lint, vacuum bags.

2. Noncompostables: includes plastics, textiles, rubber, leather, glass, tin cans, batteries, aluminum cans, metals, and other inorganics. Other inorganics include rocks/concrete/ bricks, soil, plaster, ash, etc.

4.4.1 Trace Metals in Plastics

A plastic consumer product is produced through three stages – polymer production, polymer compounding, and plastic processing (Figure 4-2). Metal can enter polymer at all the three production stages (Mark 1996). At the polymer production stage, the metal content in polymers are very low, less than 1 mg kg^{-1} polymer, while at the compounding and processing stages, metals are added as additives or through printing ink and labels (Mark 1996). Metals contained in additives are summarized in Table 4-5. Antioxidants

contain Ni. Thermal stabilizers contain Ni and Pb. Pigments and printing ink contain Cr, Cd, Cu, and Pb. Lubricants contain Mo, Ni, Pb and Zn.

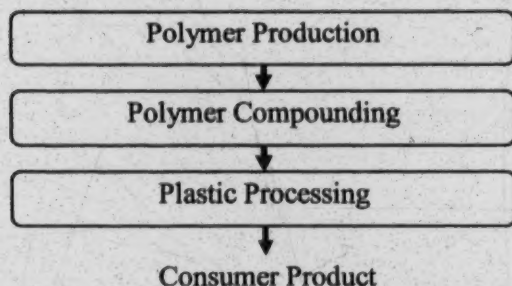


Figure 4-2. Production stages of plastic consumer products (Mark 1996).

Table 4-5. Trace metals in plastics additives (Mark 1996).

Additives	Cd	Cr	Cu	Mo	Ni	Pb	Zn	Co	Se	Hg	As
Antioxidants					x						
Thermal stabilizers					x	x					
Pigments/Printing	x	x	x			x					
Antistatics											
Fillers											
Lubricants				x		x	x				
Plasticisers											

Note: "x" indicates the metal contained in the corresponding additives.

Consumer products are made of different plastic materials such as polyethylene terephthalate (PETE), high density polyethylene (HDPE), polyvinylchloride (PVC), low density polyethylene (LDPE), and polystyrene (PS) in order to obtain desired product properties. Additives are used mainly to obtain the product characteristics needed. As a result, the trace metal content in different consumer products varies. For example, clear PETE bottles, mostly manufactured for soft drinks, have a low metal content because fewer pigments and dyes are added to these items (Mark 1996). Non-refundable

containers for oil and vinegar have a higher metal content due to larger amounts of Cd and Pb used in them (Mark 1996).

Metal concentrations in plastic products are not well documented in the literature. Only a few studies were found that investigated trace metal contents in plastics. These studies were conducted in European countries and the United States. Mark (1996) reported on metals in source-separated plastic packaging waste in European countries. The trace metal contents were analyzed using an energy dispersive X-ray fluorescence (EDXRF) method (without using acid digestion) in Mark's study. Bode et al. (1990) reported on the levels of cadmium in the plastic component of household waste in the Netherlands. The analytical method used in the study by Bode et al. was instrumental neutron activation analysis (INAA). Acid digestion was not used. Maystre and Viret (1995) reported on trace metal concentrations (recoverable concentrations, nitric acid digestion and the atomic absorption spectrophotometry method) in plastics from mixed residential MSW in Switzerland. Rugg and Hanna (1992) reported on total trace metal concentrations in plastics that were sorted from residential and commercial MSW at a landfill site in the U.S.. The total trace metal concentrations were analyzed using acid digestion and atomic absorption spectrophotometry (AAS) in the U.S. study.

The concentrations for Cd, Cr, Cu, Mo, Ni, Pb, and Zn in some plastic waste components are summarized in Table 4-6. Most plastic items included in Table 4-6 are packaging materials because non-packaging plastic items are usually less than 10% of the total plastic waste (Mark 1996). Trace metal concentrations varied with different plastic

products and different countries. For example, the Cd concentration in plastic bottles was 14 mg kg⁻¹ in European countries (in Mark's study), while Cd was not detected in plastic bottles and containers in the U.S.. The study by Maystre and Viret (1995) indicated that the concentrations for Cd, Cu, Pb, and Zn in PVC bottles were lower than in polyethylene bottles.

Table 4-6. Trace metal concentrations (mg kg⁻¹ polymer) in plastic waste.

Metal	Cd	Cr	Cu	Mo	Ni	Pb	Zn	Source
MPW ¹	50	50	Max: 150- 200	20- 30	20- 30	60- 200	110-240	
Bottles	14	16	24	NA	NA	19	240	Mark (1996)
Films:								
Shopping Bags	NA	NA	NA	NA	NA	NA	200-400 (Max:700)	
Shrink or stretch wrap	NA	NA	Up to 200	NA	NA	NA	NA	
Red, orange, and yellow plastics	50 - 1000	NA	NA	NA	NA	NA	NA	Bode et al. (1990)
PVC bottles	0.7	NA	4.6	NA	NA	8	21.7	Maystre and Viret (1995)
Polyethylene bottles	1.5	NA	14.6	NA	NA	74	57.5	
Garbage bags	5.8	NA	200	NA	NA	470	363	
Shopping bags	6.1	NA	91	NA	NA	NA	435	
PETE bottles	ND	16	31	NA	ND	61	22	Rugg and
HDPE containers	ND	57	15	NA	ND	229	63	Hanna (1992)
LDPE bags and film	ND	125	31	NA	ND	565	151	

¹ MPW – Mixed plastics waste from packaging. Hg and As in MPW are less than a few mg kg⁻¹.

NA – Not available.

ND – Not detected.

To test the trace metal levels in plastics for significance, the metal data in Table 4-6 were compared to CCME Category A trace metal limits. The Cd concentration in plastics waste in European countries ranged mainly from 0.7 to 50 mg kg⁻¹, much higher than the

CCME Category A compost limit of 3 mg kg^{-1} . The study by Bode et al. (1990) indicated that red, orange, and yellow plastics could have a Cd concentration of up to 1000 mg kg^{-1} in the Netherlands. Cadmium was not detected in plastic packaging in the U.S.. The Mo concentration in mixed plastics waste from packaging (MPW) was $20\text{-}30 \text{ mg kg}^{-1}$ (Mark 1996), higher than the CCME Category A compost limit (5 mg kg^{-1}). The maximum Cu concentration in plastic waste was up to 200 mg kg^{-1} (Mark 1996), lower than the CCME A limit (400 mg kg^{-1}). The Pb concentration in plastics in the U.S. was 565 mg kg^{-1} , higher than the CCME A limit.

4.4.2 Trace Metals in Light Bulbs

Fluorescent lamps contain mercury (Volpel 2004). The amount of mercury in fluorescent lamps varies widely, depending on the types and manufacturing methods for the lamps. Some fluorescent lamps have only 3.5 mg mercury, but some have as much as 60 mg (INFORM 2003). The amounts of mercury found in linear four-foot T8 lamps made by Philips, Sylvania, and GE were 3.5, 6-8, and 6 mg respectively; the amounts of mercury found in linear four-foot T12 lamps manufactured by Philips, Sylvania, and GE were 4.4, 9, and 9-15 mg respectively (INFORM 2003). The average amount of mercury in fluorescent lamps was about 10 mg (CEPA 2002).

Mercury in fluorescent lamps is used to produce UV energy (NEMA 2005). A very small fraction of the mercury contained in a lamp is in the form of vapor. When a lamp is broken, mercury vapor is released into the atmosphere. However, the amount of mercury retained in the solid phase was not stated (MDEP 2005). Fluorescent lamps can

contribute mercury to MSW, but whether or not these lamps are one of the significant sources of mercury in MSW compost systems is an interesting question. More studies (such as the investigation into the amount of fluorescent lamps that end up in the MSW stream) are needed to determine the contribution of lamps to the mercury content in MSW.

4.4.3 Trace Metals in Scrap Metals

It is estimated that there are more than 40,000 metallic alloys currently used (Farag 2002). Iron, aluminum, and copper are among the most widely used metals. Steel is one of the most versatile materials (Bramfitt 2002). Aluminum alloys are broadly used in products such as food packaging, beverage cans, automobile bodies, and windows (Kaufman 2002). Pure copper is used primarily for electrical and electronic products. Copper alloys are found in a very wide variety of applications. There are about 500 copper alloys currently in use (Kundig 2002).

Steel has an iron content of more than 50%, with one or more alloying elements such as Ni, Cr, and Mo (Bramfitt 2002). According to Bramfitt (2002), leaded steels have a Pb content of 0.15–0.35%. Stainless steels have a Cr content of at least 10.5%. Wear-resistant steels contain 1.5–2.5% Cr, 0.9–1.2% Mo, or 3–4% Ni. The main alloy elements in some wrought and casting aluminum alloys include Cu (0.12% - 10%), Zn (0.06% - 7%), Cr (0.09% - 0.5%), and Ni (0.5% - 2.5%). According to Kundig (2002), coppers include a minimum copper content of 99.3%. Some of the copper alloys containing trace metals are summarized in Table 4-7. Besides Cu, copper alloys contain Pb, Ni, and Zn.

Table 4-7. Some copper alloys containing trace metals (Kundig 2002).

Alloys	Metal Contained
High-copper	Cu (wrought) 96.0-99.3%; Cu (cast) > 94.0%
Brasses	Cu (55-90%), Zn (10-45%), and Ni
Bronzes	Cu (55-90%), Pb (0-8%), and Zn (0-44%)
Copper-Nickel	Cu, Ni (e.g., Cu 70%, Ni 30%)
Nickel-Silvers	Cu, Ni

Metal items found in MSW include aluminum and iron cans, lead and aluminum capsules, aluminum pastry trays, aluminum foil or pie tins, non-ferrous metals, copper electrical cables, iron covers and scraps, metallic wires, etc. Trace metal concentrations in the metal components in the American and Swiss wastes are provided in Table 4-8. The American and Swiss data showed that tin cans had a high level of Pb (exceeding the CCME A limit). The American data indicated that aluminum cans, tin cans, other ferrous and non-ferrous metals, and other aluminum products had high concentrations of Cu, Pb, Cr, Zn and Ni.

Some of the metal items have lacquers or other surface coatings. Thus, trace metals may be introduced to the items through the coatings. For instance, aluminum cans contain Cu, Cr, Ni and Zn, all of which may be attributed to alloying elements in wrought aluminum alloys. Other metals detected such as Cd, Pb, and Hg may be from red, yellow, and green pigments.

Table 4-8. Trace metal content (mg kg⁻¹) in the metal components in the U.S. and Switzerland.

Metal	As	Cd	Cr	Cu	Pb	Hg	Ni	Zn	Country
Tin cans	4.4	16	527	375	250	0.78	133	145	U.S. Cape May (Rugg and Hanna 1992)
Al cans	ND	ND	72	107	30	0.74	54	80	
Other ferrous	11.4	14	5998	157	163	0.68	320	1100	
Other Al	ND	ND	62	251	23	0.78	43	109	
Other non-ferrous	7.3	391	128	223300	28529	ND	5126	26700	
Al pastry trays	NA	0.5	NA	9	27	0	NA	29	Switzerland (Maystre and Viret 1995)
Al covers	NA	2.3	NA	4.7	72	0	NA	14	
Al beverage cans	NA	1.4	NA	39	18	0	NA	37	
Al scraps	NA	53	NA	2	84	0	NA	17	
Non-ferrous metals	NA	10	NA	1792	30010	0	NA	46827	
Copper (electrical cables)	NA	999500	NA	NA	NA	NA	NA	NA	
Iron food cans	NA	3	NA	199	380	0	NA	202	
Iron covers	NA	4.1	NA	313	520	0	NA	328	
Iron beverage cans	NA	4.1	NA	313	520	0	NA	328	
Iron scraps	NA	1.0	NA	7	15	0	NA	7.3	
Lead capsules	NA	NA	NA	NA	999000	NA	NA	NA	
Al capsules	NA	1.4	NA	39	18	0	NA	37	

ND – Not detected.

NA – Not available.

4.4.4 Trace Metals in Glass

Glasses of different properties are needed in different applications (Seward and Varshneya 2001). Metals are commonly used substances to alter the properties of glass. Lead, for example, is added to glass for brilliance and weight properties; metallic oxides

are added to glass for colourizing (HighBeam Research 2005). Three trace metals, Cr, Pb, and Zn, are found to be used in some glasses, as summarized in Table 4-9.

Green tinted glasses contain about 0.14% (1400 mg kg⁻¹) of Cr. Leaded glasses have a high level of Pb, ranging from 5.2% to 71.3%. The leaded glasses are used in lamp tubing, electron tubes, radiation shielding, capacitors, solder sealing, tungsten sealing, etc. Three types of glasses contain Zn, sealing frit (9.8% Zn), micro sheets (5.6% Zn), and opal table ware (8% Zn).

Table 4-9. Trace metal contents in different types of glasses (% by weight) (Seward and Varshneya 2001).

Glass Type	Description/Use	Pb	Zn	Cr
Soda-lime				
Typical container	Green tinted	0	0	0.14
Lead				
Corning 0010	Lamp tubing	19.1	0	0
Corning 0120	Lamp tubing	25.2	0	0
Corning 8160	Electron tubes	20.0	0	0
Corning 8161	Electron tubes	44.3	0	0
Corning 8363	Radiation shielding	71.3	0	0
Corning 8871	Capacitors	42.6	0	0
Lead sealing				
Corning 1990	To iron	34.8	0	0
Corning 7570	Solder sealing	64.3	0	0
Lead TV				
Corning 0120	Stem tubing	25.2	0	0
Corning 0137	Neck tubing	24.3	0	0
Corning 0138	Funnel	20.0	0	0
Corning 7580	Sealing frit	65.5	9.8	0
Borosilicate				
Corning 0211	Microsheet	0	5.6	0
Corning 7720	Tungsten sealing	5.2	0	0
Aluminoborosilicate				
Corning 6720	Table ware (opal)	0	8	0

In glass manufacturing, selenium is used to decolourize the green tint caused by iron impurities in glass containers (George 2005). Selenium is also used in architectural plate

glass to reduce heat transmission (George 2005). Cadmium sulfo-selenide is used in art and traffic light glasses to produce a ruby red colour.

The common glass items found in residential waste are bottles and containers. Glass items such as electron tubes are seldom found in it. According to the literature on glass manufacturing, bottles and containers can contain relatively high trace metal contents, e.g., 1400 mg kg⁻¹ of Cr in green tinted containers. However, these containers may not contribute very much to the metal content in compost due to the fact that trace metals usually exist in a silica matrix and can only be leached out to a great extent in the presence of hydrofluoric acid. In composting or analysis of compost trace metal content (usually environmentally available metals are analyzed), hydrofluoric acid is usually not involved. Thus, glass containers probably do not contribute significantly to the metal content in compost.

4.4.5 Trace Metals in Electrical and Electronic Products

Trace metals such as Pb, Hg, Cd, and As are contained in electrical and electronic products (MOEA 1995; RCBC 2005). Many components of an electrical or electronic product can contribute to the trace metal content in the product. For example, polyvinyl chloride (PVC) plastic is commonly used in electronics cabling, wiring, and housings due to its flame retardant and insulating properties (Alberta Environment 2005). Lead and Cd are often added to rigid PVC plastic parts to make them more durable (Canadian Institute of Child Health 1998). Table 4-10 shows the contents of Pb, Cu, Zn, Cd, and Cr in some components of electrical and electronic appliances (Matsutoa et al. 2004). At least one

metal content level of the components listed in the table exceeds the corresponding CCME Category A metal limit.

Table 4-10. Trace metal contents in electronic components (mg kg⁻¹) (Matsutoa et al. 2004).

Component	Pb	Cu	Zn	Cd	Cr
Power cord (TV)	7500	504000	47.3	ND	223
Wiring on Printed circuit board (WM)	5050	342000	43.6	ND	17.8
Demagnetized coil (TV)	4200	ND	73	ND	ND
Printed circuit board (TV)	9530	97200	4240	5.31	ND
Printed circuit board (R)	7280	159000	1470	ND	ND
Triple-gun colour picture tube (TV)	14100	177	59	ND	ND
Funnel glass (TV)	265000	ND	708	ND	ND
Packing (brown: R)	619	ND	327	ND	ND
Drainage hose (WM)	1360	7770	1060	ND	ND
Sound absorbing material (rubber: AC)	ND	ND	4130	ND	ND
Plastic cabinet (TV)	2250	2990	574	51.2	ND
Plastics	249	7210	803	ND	ND
Aluminum	318	859	834	ND	ND

Symbols for products: TV: TV set; WM: Washing machine; R: Refrigerator; AC: Air conditioner.

ND – Not detected.

4.4.6 Trace Metals in Batteries

Three types of batteries are commonly used by householders, i.e. wet-cell, dry-cell non-rechargeable, and dry-cell rechargeable (Waste Watch 2005). Trace metals contained in these batteries are summarized in Table 4-11. These trace metals include Zn, Cd, Pb, Hg, Cu, Co, and Ni. Zinc, Cd, and Pb are normally used in anodes, and Hg, Cu, Co, and Ni are mainly used in cathodes (Linden 2002). The trace metals used in electrodes are very high in purity. For instance, zinc powder (containing 99.99% of Zn) is used in making the alkaline anode of alkaline manganese batteries (Scarr et al. 2002).

Dry-cell non-rechargeable batteries are the most common batteries used in households.

The applications of these batteries are given in Table 4-11. Currently only a small

percentage of used batteries are recycled. In the UK, 20,000 - 30,000 tonnes of waste batteries were generated annually, but fewer than 1,000 tonnes were recycled (Waste Watch 2005).

Table 4-11. Trace metals contained in batteries used by householders (Waste Watch 2005).

Type	Battery Name	Application	Metal contained
Wet-cell	Lead acid	Power vehicles and used by industry	Pb
Dry-cell non-rechargeable	Zinc carbon	Flashlights, clocks, shavers and radios	Pb, Zn, and Cd
	Zinc chloride	Flashlights, clocks, shavers and radios	Zn
	Alkaline	Personal stereos, radio-cassette	Zn, Cd, and Hg
	manganese	players	
	Mercuric oxide (button cell)	Hearing aids, pacemakers, photographic equipment	Hg
	Zinc air (button cell)	Hearing aids and radio pagers	Zn
	Silver oxide (button cell)	Electronic watches and calculators	Zn, Hg, and Ni
Dry-cell rechargeable	Lithium (button cell)	Watches and photographic equipment	Cu, Pb, and Ni
	Nickel cadmium (NiCd)	Cordless power tools, personal stereos, portable telephones, lap-top computers, shavers, motorised toys	Ni, Cd and Co
	Nickel metal hydride (NiMH)	Cordless power tools, personal stereos, portable telephones, lap-top computers, shavers, motorised toys	Ni, Co, and Cr
	Lithium ion (Li-Ion)	Cell phones and laptops	Co, Ni, and Pb

4.4.7 Trace Metals in Dust

Residential dust can contain hundreds of chemicals, some of which are trace metals, such as Pb, Cd, and Hg (SWA 2001). The literature review indicated that household dust can have high contents of Pb, Cd, and Hg. Trace metal concentrations in house and street dusts from some studies are presented in Table 4-12. As shown in the table, Ottawa

geometric mean concentrations for Pb, Cd, and Hg in the house dust were 233, 4.42, and 1.73 mg kg⁻¹ respectively (Rasmussen et al. 2000), which were much higher than the CCME Category A limits. However, the concentrations for Pb, Cd, and Hg in street dust were lower than in the house dust and the CCME Category A limits. Rasmussen et al. (2001) reported that the metal concentrations (90th percentiles) for Pb, Cd, and Hg in garden soil in Ottawa were 42, 0.27, and 0.055 mg kg⁻¹ respectively, which were much lower than in Ottawa house dust and the CCME Category A limits. The household dust contained higher Pb, Cd and Hg contents than street dust and garden soil.

Table 4-12. Trace metal concentrations in house dust of different cities (mg kg⁻¹).

Metal	Pb	Cd	Hg	Zn	Cu	As	Cr	Ni	Mo	Co
House dust (Ottawa, 90 th percentile) ¹	969	15.3	6.57	1226	382	13	157	103	4	12
House dust (Ottawa, geom. mean) ²	233	4.42	1.73	628	171	4.9	75.4	53.6	1.96	8.40
Street dust (Ottawa, 90 th percentile) ¹	68	0.6	0.06	184	188	2	59	19	2	11
House dust (Hettstedt, Germany) ³	125.3	2.6	NA	NA	NA	2.6	NA	NA	NA	NA
House dust (median) ⁴	164	6.75	1.69	NA	170	5.15	NA	NA	NA	NA
House dust (Australia, geom. mean) ⁵	85.2	1.9	NA	437	103	NA	64.3	15.6	NA	NA

¹ Rasmussen et al. (2000). Values reported are 90th percentiles to represent the maximum value most likely to be encountered. Within about 300 km around Ottawa, there are no mining and smelting activities. Lead was phased out of virtually all Canadian gasoline by 1990 (Marchi 1996).

² Rasmussen et al. (2001). Values reported are geometric mean concentrations. Indoor dust was sampled from 50 residences located in 10 neighborhoods across Ottawa.

³ Meyer et al. (1999). Values reported are median. Hettstedt is a city in eastern Germany with a long history of mining and smelting of nonferrous ores.

⁴ Loiy et al. (2002). Sampling location and country are not specified.

⁵ Chattopadhyay et al. (2003). Values reported are geometric mean concentrations. House dust was collected from 82 residential homes within the Sydney metropolitan area.

Note: NA – Not available.

ND – Not detected.

A study by Loiy et al. (2002) also indicated that Pb, Cd, and Hg contents in household dust were higher than the CCME Category A limits. The concentrations for Pb and Cd in house dust in Germany and Australia were lower than the CCME A limits, but Pb and Cd concentrations in German house dust were close to the CCME A limits.

Household dust could contribute significantly to the concentrations of Pb, Cd, and Hg if the generation rate of household dust was large enough. An investigation into the average generation rate of house dust in Edmonton is ongoing.

4.4.8 Trace Metals in Textiles, Rubber, Leather, and Treated Wood

Textile, rubber, leather, and wood waste components are usually not classified as separate categories in waste audits. Thus, information about these materials is scarce. The available results from some waste audits are provided in Table 4-13.

Table 4-13. The proportion (wet weight, %) of textiles, rubber, leather, and wood in MSW in different cities.

Material	Geneva MSW ¹	U.S. Cape May MSW ²	U.S. Monongalia MSW ³	U.S. Charleston MSW ³
Wood		3.8	10.7	10
Leather	0.017 ⁴		NA	NA
Rubber		5.3 ⁵	NA	NA
Textile	0.005		5.8	3

¹ Maystre and Viret (1995). Switzerland.

² Rugg and Hanna (1992). U.S..

³ Martin et al. (1995). U.S..

⁴ 0.017% for wood/leather/rubber

⁵ 5.3% for leather/rubber/textile

NA - Not available.

The proportion of these materials in MSW varied with different cities. The proportion of textiles ranged from 3% to 5.8% in U.S. cities (Charleston and Monongalia), but it accounted for only 0.005% in Geneva. Wood, leather and rubber were pooled together as one category in Geneva, while in the U.S. Cape May study, textiles, leather and rubber were grouped into one category. It is noticed that the proportion of textiles, wood, leather, and rubber in Geneva was much lower than that in the U.S. cities.

Trace Metals in Textiles

Trace metals may be introduced into textiles through dyes containing metals such as Zn, Ni, Cd, and Co (USEPA 1997). Metals can be an integral part of a dye molecule, but in most dyes, metals are simply impurities introduced during dye manufacture. For example, mercury may be used as a catalyst in manufacturing certain dyes, and as a result, Hg may be present in dyes.

Trace Metals in Rubber

Trace metals such as Pb, Zn, Ni, Se, and Cd are added into rubber in compounding and mixing processes (USEPA 1995a). Some chemicals containing trace metals are used as processing aids and accelerators (zinc compounds), activators (nickel compounds), age restorers (selenium, zinc, and lead compounds), accelerator activators (zinc and lead compounds), and miscellaneous ingredients (cadmium compounds).

Trace Metals in Leather

Some trace metals are introduced into leather in the leather tanning process. One of the most common tanning agents is trivalent chromium. The chrome tanning process accounts for approximately 90% of the U.S. tanning process. Cadmium is also used as a leather tanning agent along with other metals such as Ni, Pb, and As (DTMRP 2005). As a result, leather products can contain Cr, Cd, Zn, Ni, and As.

Trace Metals in Treated Wood

Preserved wood may contain As, Cr, Cu, and Zn after being treated with preservatives including water-borne inorganics like chromated copper arsenate (CCA) and ammoniacal copper zinc arsenate (ACZA) (USEPA 1995b). Water-borne inorganic solutions constitute approximately 78 % of all preservatives used in the U.S. (USEPA 1995b). Painted wood may contain trace metals such as Pb, Zn, Cd, Cr, Mo, and Cu depending on the paint colour (USEPA 1995c).

Trace Metal Concentrations from Waste Audit Studies

Waste audits done in the U.S. and Switzerland provided numerical information on trace metal concentrations in textiles, rubber, leather, and wood wastes. The results of the waste audits are provided in Table 4-14. The mercury concentration in the U.S. wood waste was 2.58 mg kg^{-1} . Mercury was not detected in Swiss wood waste. The difference between the American and Swiss cities may be caused by several factors such as differing legislation and waste management systems. It can be seen from Table 4-14 that wood can

be a source of As and Pb. Rubber and leather contribute greatly to Cd, Pb, and Zn contents. Textiles, rubber, and leather can contribute significantly to Cd and Cr.

Table 4-14. Metal concentrations in textiles, rubber, leather, and wood waste (mg kg^{-1}).

Country	Metal	As	Cd	Cr	Cu	Pb	Hg	Ni	Zn
U.S. Cape May (Rugg and Hanna 1992)	Textile/rubber/ leather	1.0	23	469	30	58	0.33	6	806
	Wood	40.3	ND	62	38	129	2.58	ND	ND
Switzerland (Maystre and Viret 1995)	Wood	NA	2.0	NA	13	309	0	NA	70
	Rubber	NA	8.4	NA	28	197	0	NA	7028
	Leather	NA	4.9	NA	74.5	372	0	NA	436
	Textiles	NA	2.2	NA	8.7	19	0	NA	42.9

ND – Not detected.

NA – Not available.

4.4.9 Trace Metals in Paper

Paper ink may contribute to trace metal contents in printed papers. Information about the composition of ink is proprietary and thus is not well reported in the literature. Metal salts are normally used as ink pigments although some pigments are plastics or vegetable dyes (About 2005). Metals are associated with the colour of pigments, e.g., Hg with red; Cd with red, orange, and yellow; Se with red and orange; Zn with yellow and white; Pb with yellow, green, and white; Cr with yellow and green; Co with blue; and Cu with green and blue.

Trace metal concentrations in waste papers from MSW characterization studies in the U.S. and Switzerland are provided in Table 4-15. The concentrations for As, Cd, Cr, Cu, Pb, Hg, Ni, and Zn in U.S. waste papers were below the CCME limits for Category A compost. However, the Cd content in Other Waste Paper (8.4 mg kg^{-1}) and Pb content in Packaging Waste (316 mg kg^{-1}) in Switzerland well exceeded the CCME category A limits (3 and 150, respectively). The Cd concentrations in all types of waste papers in

Switzerland were quite different from those in the U.S.. The Cd contents in Switzerland ranged from 2.1 to 8.4 mg kg⁻¹, while Cd was not detected in the U.S. waste papers. The difference might be caused by several factors such as culture, legislation, and waste collection systems. Trace metal concentrations in waste paper may be subject to regional variability.

Table 4-15. Trace metal contents (mg kg⁻¹) in waste papers in the U.S. and Switzerland.

Country	Type of waste paper	As	Cd	Cr	Cu	Pb	Hg	Ni	Zn
U.S. (Rugg and Hanna 1992)	Newspaper	0.2	ND	ND	25	ND	0.41	ND	83
	Cardboard	0.3	ND	ND	17	24	0.22	8	73
	Kraft	0.4	ND	7	15	22	0.19	ND	43
	High-grade	0.7	ND	ND	8	ND	0.12	ND	31
	Magazines	0.5	ND	4	52	ND	0.1	ND	99
	other	0.6	ND	7	79	14	0.1	ND	88
Switzerland (Maystre and Viret 1995)	Newspaper	NA	2.5	NA	12	23	0	NA	41
	Packaging	NA	2.1	NA	44.3	316	0	NA	26.7
	Other	NA	8.4	NA	280	39	0	NA	35
	Other cardboard	NA	2.3	NA	72	70	0	NA	75.3
	Packaging cardboard	NA	2.2	NA	84.3	43	0	NA	59.7

ND – Not detected.

NA – Not available.

4.4.10 Trace Metals Distribution among MSW Components

A study by Rugg and Hanna (1992) provided valuable information on trace metal distribution among MSW components (Table 4-16). Total trace metal concentrations were analyzed in this study using acid digestion and atomic absorption spectrophotometry (AAS). The results indicated that sources of trace metals are mainly noncompostable MSW components such as batteries and ferrous and nonferrous metals. Textiles, rubber, and leather were an important source of Cd in MSW, contributing about

33% of the total Cd content. Wood contributed 58% of the total As in MSW. Batteries contributed about 89% of the total Hg and 55% of the total Zn in MSW. Ferrous and nonferrous metals (other than tin and aluminum cans) were important sources of As, Cd, Cr, Cu, Pb, Ni, and Zn. Noncompostables contributed to more than 86% of the total content of As, Cd, Cr, Cu, Pb, Hg, Ni, and Zn in MSW.

Table 4-16. Trace metal distribution (%) among MSW components (Rugg and Hanna 1992).

MSW components	As	Cd	Cr	Cu	Pb	Hg	Ni	Zn
Total Noncompostable	86.1	97.1	99.1	93.2	88.9	93.7	92.5	89.0
PET bottles	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0
HDPE containers	0.0	0.0	0.1	0.0	0.9	0.0	0.0	0.1
LDPE bags and films	0.6	0.0	1.2	0.2	12.9	0.1	0.0	0.9
Other plastic	1.4	20.8	0.2	0.2	1.5	0.1	0.0	1.4
Textile/rubber/leather	2.0	32.8	8.0	0.4	2.5	0.4	1.2	9.0
Wood	58.0	0.0	0.8	0.3	4.0	2.1	0.0	2.0
Glass containers	0.0	0.0	0.0	0.0	3.0	0.2	0.0	0.0
Tin cans	2.6	7.1	2.7	1.4	4.5	0.3	7.5	0.5
Batteries	0.4	2.1	0.0	2.8	0.3	88.9	0.0	55.0
Other ferrous materials	18.8	16.4	85.4	1.6	5.8	0.6	49.8	10.2
Aluminum cans	0.0	0.0	0.2	0.2	0.2	0.1	1.3	0.1
Other aluminum	0.0	0.0	0.2	0.6	0.2	0.2	1.6	0.2
Other nonferrous materials	0.5	17.9	0.1	85.4	51.7	0.0	30.4	9.4
Other inorganics	1.7	0.0	0.3	0.1	1.5	0.7	0.7	0.2
Total Compostable	13.9	2.9	0.9	6.8	11.1	6.3	7.5	11.0

4.4.11 The Contribution of Biosolids to Trace Metal Content

In the co-composting of MSW and biosolids, residential solid waste and de-watered sewage biosolids are used as the feedstock. To test the significance of the contribution of biosolids to the trace metal content in compost, a comparison among metal concentrations in Edmonton composts produced from biosolids, MSW/biosolids, and yard waste was made. The result indicated that the biosolids compost was higher than the

MSW/biosolids compost in concentrations of Cd, Co, Mo, Se, and Cr (Figures 4-3 and 4-4), implying that biosolids can be a significant source of Cd, Co, Mo, Se, and Cr.

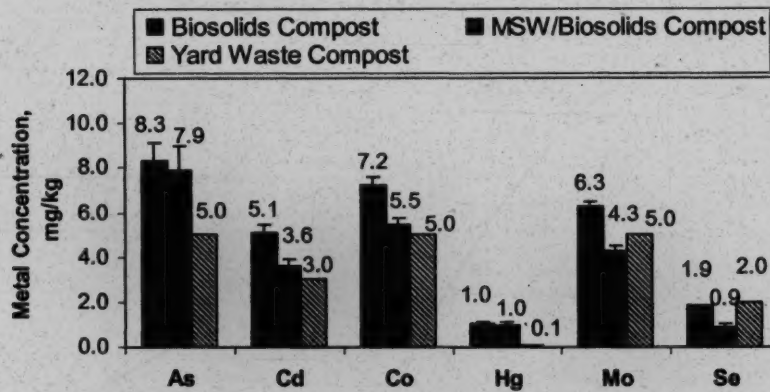


Figure 4-3. Comparison of Compost As, Cd, Co, Hg, Mo, and Se Concentrations (Y bar: ± 1 standard error).

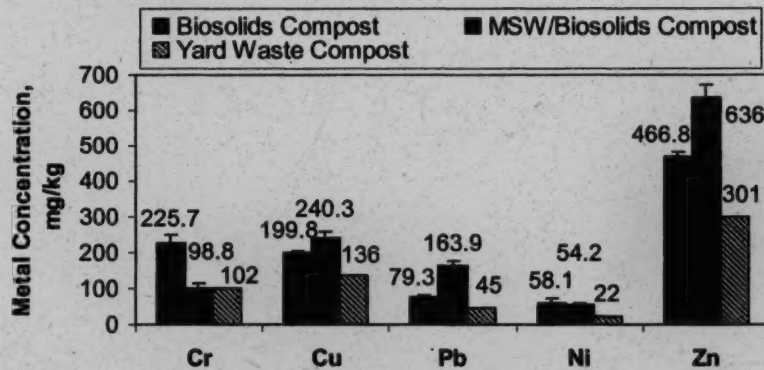


Figure 4-4. Comparison of Compost Cr, Cu, Pb, Ni and Zn Concentrations (Y bar: ± 1 standard error).

4.4.12 The Contribution of Equipment to Trace Metal Content

It was reported that compost-processing equipment could contribute trace metals to composted material (Richard et al. 1993), e.g., screens, turners, and mixing drums. A study on the contribution of the mixing drums of the Edmonton Composting Facility to trace metal content was carried out. The liner of mixing drums is subject to pressure,

friction, and impact. Thus, liner deterioration occurs. The liner is also subject to corrosion when in an aerated environment with a pH of 5.5 to 6.5 and in contact with materials with a moisture content of 40% to 60%. The liner is subject to both chemical attack and physical deterioration, so-called erosion-corrosion. Corrosion is increased because of the abrasive action of a moving stream. On the other hand, erosion is enhanced due to the formation of loose dust on the surface.

The Edmonton mixing drums had a 4.9 m inside diameter and a 64 m length. Each drum lost 1.59 mm of carbon steel liner per year (Latta 2005). Detailed information about this investigation is provided in Appendix C. The result indicated that mixing drums could contribute to 4.3% to 10.5% of the total Cu content in compost. Mixing drums may not be the key contributor to the Cu content in compost.

4.4.13 Trace Metal Mass Flows in MSW Compost System

A trace metal mass flow diagram (Figure 4-5) was developed based on the data on trace metal concentrations, moisture content, and process quantity from the ECF and relevant information from the literature. The calculation for developing the diagram is provided in Appendix D. The mass flow diagram is based on 93000 tonnes of dry residential MSW feedstock (average Edmonton annual MSW input). Both concentration and mass of trace metals are given in the diagram. Summaries of metal concentrations, masses, and distribution among outputs are provided in Table 4-17, Table 4-18, and Table 4-19 respectively.

Table 4-17 indicates that concentrations of As, Cd, Ni, and Zn in biosolids are higher than those in MSW. Concentrations of Cr, Cu, Pb, and Hg in biosolids are lower than those in MSW. Table 4-18 shows that MSW contributes to most of the trace metal content in MSW and biosolids co-composting systems. Table 4-19 indicates that 5.7% to 40.9% of the total mass of trace metals in feedstocks ends up in uncured compost. Over 40% of the total As input is retained in uncured compost, the highest level. Only 5.7% of the total Hg input is retained in uncured compost, the lowest level.

The trace metal flow diagram provides useful information on the metal flows in a typical MSW/biosolids co-composter, but some limitations exist.

- The MSW characterization study in the U.S. Cape May County (Rugg and Hanna 1992) was done in 1992. The current MSW may be different from what it was over ten years ago in terms of metal content in consumer products because environmental regulations have undergone changes. The characteristics of MSW may vary significantly in different countries or regions.
- For MSW feedstock and primary and secondary residuals, metal concentrations for Co, Mo, and Se were not available in the literature.
- Information on the ECF household hazardous waste (HHW) from the tip floor, ferrous metals recovered after the primary screening, and metal losses during the composting process are not available.
- Only the metal concentrations in biosolids and uncured compost are commercial production data from the ECF. The other metal concentration data were either calculated based on the results of Edmonton waste sorting or adapted from U.S.

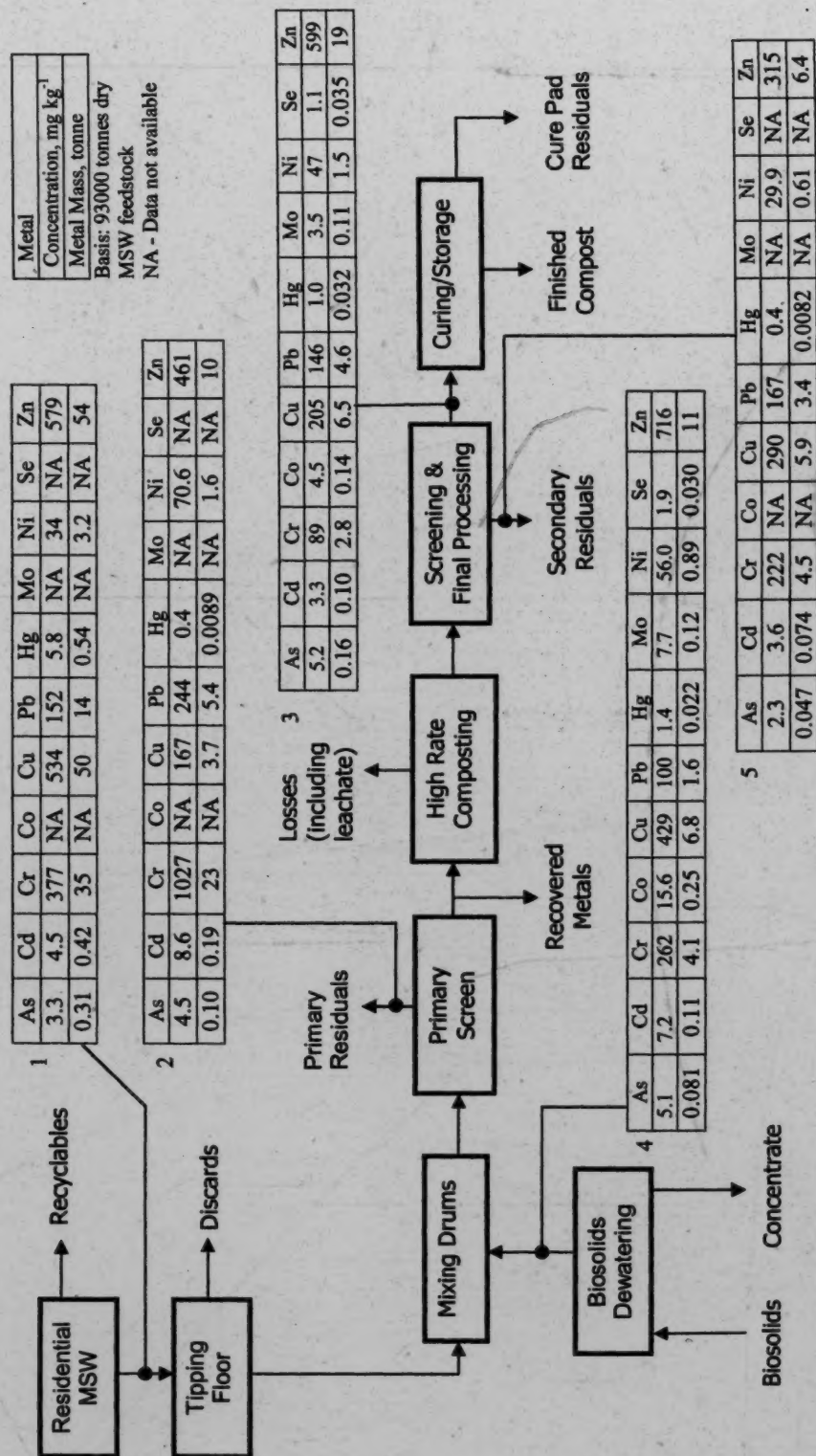


Figure 4-5. Trace metal mass flow diagram (Concentration data sources: ¹ Rugg and Hanna (1992), ² Rugg and Hanna (1992), ³ TransAlta (2001), and City of Edmonton (2002), ⁴ TransAlta (2001), and City of Edmonton (2002), ⁵ Rugg and Hanna (1992), TransAlta (2001), and City of Edmonton (2002), ⁶ Bittner (2005), ⁷ TransAlta (2001) and City of Edmonton (2002)).

Table 4-17. Metal concentrations (mg kg^{-1}) in input and output material streams.

	Material Stream	As	Cd	Cr	Co	Cu	Pb	Hg	Mo	Ni	Se	Zn
Input	MSW	3.3	4.5	377	NA	534	152	5.8	NA	34	NA	579
	Biosolids	5.1	7.2	262	15.6	429	100	1.4	7.7	56.0	1.9	716
Output	Primary residuals	4.5	8.6	1027	NA	167	244	0.4	NA	70.6	NA	461
	Secondary residuals	2.3	3.6	222	NA	290	167	0.4	NA	29.9	NA	315
	Uncured compost	5.2	3.3	89	4.5	205	146	1.0	3.5	47	1.1	599

NA - Not available.

Table 4-18. Mass of metals (tonnes) in input and output material streams.

	Material Stream	As	Cd	Cr	Co	Cu	Pb	Hg	Mo	Ni	Se	Zn
Input	MSW	0.31	0.42	35	NA	50	14	0.54	NA	3.2	NA	54
	Biosolids	0.081	0.11	4.1	0.25	6.8	1.6	0.022	0.12	0.89	0.03	11
Output	Input total	0.39	0.53	39	NA	57	16	0.56	NA	4.1	NA	65
	Primary residuals	0.1	0.19	23	NA	3.7	5.4	0.0089	NA	1.6	NA	10
	Secondary residuals	0.047	0.074	4.5	NA	5.9	3.4	0.0082	NA	0.61	NA	6.4
	Uncured compost	0.16	0.1	2.8	0.14	6.5	4.6	0.032	0.11	1.5	0.035	19
	Total of above three	0.31	0.36	30	NA	16	13	0.049	NA	3.7	NA	35
	Others ¹	0.08	0.17	8.8	NA	41	2.2	0.51	NA	0.38	NA	30

Note: Assume 93000 tonnes of dry MSW feedstocks. Metal input from other sources such as processing equipment is not included.

NA - Not available.

¹ Including household hazardous waste (HHW) from tip floor, ferrous metals recovered after primary screen and metal losses during the whole process. Metal Mass for "Others" (tonne) = Input (including MSW and biosolids) - Output (including HHW, loss and ferrous metals).

Table 4-19. Metal distribution among outputs (%).

Material Stream	As	Cd	Cr	Co	Cu	Pb	Hg	Mo	Ni	Se	Zn
Input Total	100.0	100.0	100.0	NA	100.0	100.0	100.0	NA	100.0	NA	100.0
Primary residuals	25.6	35.8	58.8	NA	6.5	34.6	1.6	NA	39.1	NA	15.4
Secondary residuals	12.0	14.0	11.5	NA	10.4	21.8	1.5	NA	14.9	NA	9.8
Others	21.5	31.3	22.5	NA	71.7	14.1	91.3	NA	9.3	NA	45.5
Uncured compost	40.9	18.9	7.2	NA	11.4	29.5	5.7	NA	36.7	NA	29.2

Note: Metal Distribution (%) = Mass of the material / Total mass of inputs $\times$ 100.

NA - Not available.

studies (e.g., MSW feedstock and primary residuals). The actual metal concentrations for these materials in Edmonton might vary significantly from those calculated or taken from the literature.

4.5 Conclusions

- Noncompostables could contribute to more than 86% of the total content of As, Cd, Cr, Cu, Pb, Hg, Ni, and Zn in MSW.
- Aluminum and tin cans and other ferrous and non-ferrous metals have high Cu, Pb, Cr, Zn, and Ni concentrations and can be important sources of trace metals in MSW.
- Fluorescent lamps contain mercury ranging from 3.5 to 60 mg depending on lamp types and manufacturers. Fluorescent lamps can contribute mercury to MSW, but whether or not these lamps are one of the significant sources of mercury in MSW compost systems is an interesting question. Further research is needed to determine the contribution of lamps to the mercury content in MSW.
- The contents of Pb, Cu, Zn, Cd, and Cr in some components of electrical and electronic products are much higher than the CCME Category A limits. Electrical and electronic products can be one of the important sources of trace metals.
- Trace metals Pb, Zn, Cd, Hg, Ni, Cr, and Co are used in manufacturing different types of batteries. Pure metals are used mainly as electrodes in batteries, e.g., zinc powder of 99.99% purity in alkaline manganese batteries.

- Dust generated from household contains high contents of Pb, Cd, Hg, and Zn, but the contribution of house dust to the metal content in compost is uncertain because the generation rate of house dust is unknown.
- Treated wood can be a source of As and Pb. Rubber and leather contribute greatly to Cd, Pb, and Zn contents. Textiles, rubber, and leather can contribute significantly to Cd and Cr contents. Paper ink can contribute to trace metal contents in printed paper.
- Mixed plastics waste from packaging (MPW) can have relatively high Cd, Mo, and Pb contents.
- Glass items, such as green tinted containers, contain relatively high trace metal contents, but they may not contribute much to the metal content in compost because trace metals usually exist in a silica matrix.
- Biosolids can be a significant source of Cd, Co, Mo, Se, and Cr. Composting mixing drums could contribute to 4.3% to 10.5% of the total Cu content in Edmonton MSW compost.
- 5.7% to 40.9% of the total input of trace metals in composting feedstocks can end up in uncured compost. Over 40% of the total As input is retained in uncured compost, the highest level. Less than 6% of the total Hg input is retained in uncured compost, the lowest level.

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Chapter 5 Composting Feedstock and Compost Trace Metal Content Analysis

5.1 Introduction

Mixed MSW composting feedstocks include materials such as food scraps, yard trimmings, paper, cardboard, plastics, glass, and metal. Food and yard wastes, which account for 28.9% and 23.3% of residential MSW, respectively (Schubert and Gannon 2001), are primary organic fractions to be composted. Materials such as plastics, glass, and metal, which are non-biodegradable, are simply foreign matter to compost. Thus these materials need to be removed from compost systems as much as possible. Paper and cardboard are normally the targets of fibre recycling programs, but they can be still found in residential MSW. Paper and cardboard account for 16.5% of residential MSW, the third largest waste component, exceeded only by food and yard wastes (Schubert and Gannon 2001). Paper and cardboard are biodegradable; they can be converted to compost.

Food and yard wastes normally contain low levels of trace metals; compost of low metal content can be produced from these materials. Some paper and cardboard, however, contain relatively high levels of trace metals. Maystre and Viret (1995) reported that some paper contained high Pb and Cu contents, e.g., 316 mg kg⁻¹ of Pb in packaging and 280 mg kg⁻¹ of Cu in Other Waste Paper. Trace metals can be added to paper through printing inks (MEI 2005) and coating materials and fillers such as kaolin (EKA 2005). Paper and cardboard may have an impact on trace metal concentrations in compost.

Most of plastics, glass, and metal are removed from compost systems. Some plastics, glass, and metal, however, remain in final compost products. The plastics, glass, and metal that are present in compost are called foreign matter. Page (2002) reported that plastics, glass, and metal accounted for about 1.5%, 0.5%, and 0.1% (dry weight basis) of the final screened compost in her samples, respectively.

The literature review indicated that plastics and glass can contain trace metals. Coloured labels and logos which contain metal-containing pigments and dyes can contribute to trace metal content in plastic. Mixed plastic waste from packaging could contain as much as 50 mg kg⁻¹ of Cd and 60-200 mg kg⁻¹ of Pb (Mark 1996). Glass contains trace metals mainly due to the addition of property altering substances, e.g., lead for brilliance and metallic oxides for imparting colour (HighBeam Research 2005).

This study was carried out to determine the trace metal contents of some feedstock materials for composting – papers, cardboards, plastic materials, and glasses of different types – and to determine whether these materials contribute significantly to the metal content in compost. Emphasis was put on the effects of colourants and fillers on the trace metal contents in paper, cardboard, plastics, and glass.

Trace metal contents in plastic, glass, and metal foreign matter sorted from a final compost product were analyzed to investigate the effects of this foreign matter on compost metal concentrations. Trace metal contents in compost fractions of various

particle sizes were analyzed to determine the possibility of reducing trace metal levels in compost by manipulating the particle sizes of compost.

5.2 Materials and Methods

Three categories of materials were analyzed for trace metal contents in this study. The first category was feedstock materials from Edmonton Material Recovery Facility (MRF). This category included paper, cardboards, plastic, and glass materials of various types. The secondary category included plastic, glass, and metal foreign matter and a compost portion that was sorted from a final compost product. The third category was compost fractions of various particle sizes.

All feedstock materials collected from the MRF were prepared manually using tools including snips, scissors, a hammer, etc. Mechanical sample preparation was avoided in order to minimize the contamination from machines.

Plastic, glass, metal foreign matter, and compost from which foreign matter had been sorted out were obtained from a previous study done in 2002 (Page 2002). These materials were not contaminated through the use of any metallic equipment or tools. Contact of the samples with metals was minimized to avoid contamination.

Compost fractions of various particle sizes were obtained through sieving screened and unscreened compost samples. The screened and unscreened compost samples were collected from compost piles at the Edmonton Composting Facility. Compost sampling,

preparation, and sieve analysis were performed in accordance with related TMECC methods (2001).

All containers and bags used in this study were plastic and brand new. Repeatedly used tools were soap-cleaned before use. New plastic sheets were used whenever samples were mixed and split. All samples for analysis were sent to a commercial lab. The analytical methods used by the lab were in accordance with US EPA methods, as detailed in Section 5.1.5.

5.2.1 Apparatus

Feedstock Sampling and Sample Preparation

MaxSteel Aviation Snips (the Stanley Works, New Britain, CT U.S.) with chrome molybdenum alloy steel blades were used for cutting rigid plastics and cardboard. A utility knife (OLFA model SKB-2, Japan) was used for cutting cardboard. Stainless steel blade kitchen scissors were used for cutting paper. A Workforce brand tubular steel hammer was used for breaking glass.

Compost Sampling and Sample Preparation

A stainless steel shovel was used to cut into compost piles. Plastic shovels and trowels were used to collect, split, and prepare samples. Roughtotes (68 L) and GLAD plastic garbage bags (65 L) were used for storing the compost. Plastic bags with seals (Ziplock, various sizes), clear plastic sheets, plastic spoons, sticky labels, and marking tapes were also used.

Compost Sieve Analysis

Canadian Standard Sieve Series (9.5 mm, 4.0 mm, and 2.0 mm; brass frame and mesh; the W.S. Tyler Company of Canada, Limited) and U.S.A. Standard Testing Sieves (6.3 mm and 0.85 mm; ASTM E-11 specification; Fisher Scientific Company) were used in the analysis. An RX-24 Portable Sieve Shaker (W.S. Tyler Incorporated, Gastonia, N.L.) was used for screening the samples. A Fisher 500 series Isotemp Gravity-Convection Oven (temperature range: 40-200 °C; control sensitivity: $\pm 0.5^{\circ}\text{C}$; Fisher Scientific), Fisher desiccator cabinets (Fisher Scientific), and a Mettler PC 2200 Balance (0-2200 g $\pm$ 0.01g; Mettler Instrument AG) were used for drying and weighing.

5.2.2 Sample Collection

Feedstock Materials Collection

As mentioned in Section 5.1, colourants (pigments or dyes) in printing inks and additives can be an important contributor to the metal content in paper and plastics. Metallic oxide pigments are one of the most important sources of trace metals in glass containers. To determine the effects of colourants on trace metal contents in these materials, paper, cardboard, plastics and glass samples were collected from the Edmonton Material Recovery Facility (MRF) production line and material piles on December 20, 2005. The samples collected are summarized in Table 5-1.

Sorted Foreign Matter and Compost Fractions

Sorted foreign matter and compost fractions were obtained from a previous study – Foreign Matter in MSW Compost (Page 2002). Page sorted Edmonton compost samples into fractions of plastics, glass, metal, and remaining compost. These fractions were donated by Page and were analyzed for trace metal contents.

Table 5-1. Samples collected from Edmonton MRF.

Materials	Sample	Number of samples	Sample weight (per sample)	Rationale
Paper	With only black ink ¹	2	2 kg	Black ink may contain small amounts of trace metals.
	With coloured ink ²	2	2 kg	Coloured inks may contain higher amounts of trace metals (Cd, Hg, Pb, Cr, Cu, Pb, and Zn).
	Glossy	2	2 kg	Kaolin used to produce glossy paper may contain trace metals.
Cardboard	With only black ink ¹	2	3 kg	May contain small amounts of trace metals.
	With coloured ink ²	2	3 kg	Coloured inks may contain higher amounts of trace metals (Cd, Hg, Pb, Cr, Cu, Pb, and Zn).
	Glossy	2	3 kg	Kaolin used to produce glossy cardboard may contain trace metals.
Plastics	Coloured	2	1 kg	May contain Pb, Cr, Zn, Cu, Hg, Cd, & Se because of addition of additives.
	Coloured with printing ink ³	2	1 kg	Determine the impact of printing inks on metal content.
Glass	Brown & yellow	2	4 kg	May contain Pb & Cr.
	Blue & green	2	4 kg	May contain Cu & Cr.
Total		20		

¹ Pieces of paper with black words/images on them were used for the sample.

² Pieces of paper with coloured words/images on them were used for the sample.

³ Pieces of plastic with coloured words/logos/images on them were taken for the sample.

Compost Collection

Four composite compost samples (48 L each) were taken from the ECF curing site in December 2005. The compost was produced in 2003 and had been cured for two years. Two of the four samples were taken from compost curing piles. The other two samples were collected from compost piles that had passed through a 6.3 mm trommel screen. The two samples taken from compost piles that did not pass through a 6.3 mm trommel screen are called "unscreened compost samples" hereafter. The two samples taken from compost piles that passed through a 6.3 mm trommel screen are called "screened compost samples." Compost sampling was carried out in accordance with 02.01-B Selection of Sampling Locations for Windrows and Piles (TMECC 2001).

5.2.3 Sample Preparation

Feedstock Material Preparation

All materials were air-dried for two days before preparation. Paper, cardboard, and plastic sub-samples were prepared by selecting and cutting out the needed portions from the air-dried materials. The sub-samples were cut into small pieces 5×5 mm in size. 100-cm³ samples for trace metal analysis were then obtained from the sub-samples (5×5 mm in size) using a quartering method. For example, paper portions with double-sided black or coloured images were selected and cut out for preparation of black or coloured ink sub-samples. Each sub-sample was cut into pieces 5×5 mm in size, and about 400 cm³ (loose volume) of the sub-sample was obtained. A 100-cm³ loose sample was prepared from the sub-sample for trace metal analysis. Figures 5-1 and 5-2 illustrate how one of the coloured paper portions was selected and cut out for preparation of the coloured paper

sub-sample. The paper, cardboard, and plastic samples that were sent for laboratory analysis are described in Table 5-2.

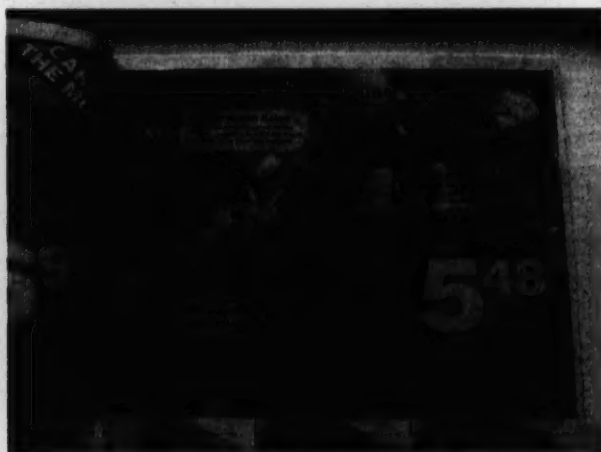


Figure 5-1. A selected portion constituting part of the coloured paper sub-sample.
(Dimensions of the selected portion: 170 mm × 205 mm)



Figure 5-2. A portion cut out for preparation of the coloured paper sub-sample.
(Dimensions: 170 mm × 205 mm)

Table 5-2. Description of samples sent for trace metal analysis.

Samples	Description
Paper (newsprint) with black ink	Paper with double-sided, black-printed images
Paper (newsprint) with coloured ink	Paper with double-sided, coloured-printed images
Glossy paper (magazine) with coloured ink	Glossy paper with double-sided, coloured-printed images
Cardboard with black ink	Cardboard with single-sided, black-printed images
Cardboard with coloured ink	Cardboard with single-sided, coloured-printed images
Glossy cardboard with coloured ink	Glossy cardboard with single-sided, coloured-printed images
Coloured plastic without ink	Coloured plastic without printed images
Coloured plastic with coloured ink	Coloured plastic with single-sided, coloured-printed images
Glass with brown & yellow colours	Consists of 50% brown and 50% yellow coloured glasses (by weight)
Glass with blue & green colours	Consists of 50% blue and 50% green coloured glasses (by weight)

Sorted Foreign Matter and Compost Fractions

There were 45 bags of sorted foreign matter and compost samples available from Page's study (2002). The foreign matter fractions in each bag were very small in mass (only several pieces), not enough for chemical analysis. Thus, all materials of the same type, e.g., plastic, were pooled together for trace metal analysis. Only three samples were formed: plastics (film and chips), glass, and metal. In addition to foreign matter samples, sorted compost fractions were also pooled together as a compost fraction sample for trace metal analysis.

Compost Preparation

Each of the 48-L screened and unscreened compost samples was mixed thoroughly and split to approximately 12 L using the quartering method. Each 12-L sample was then subdivided into roughly 500-cm³ sub-samples for sieve analysis. The compost sample

preparation was carried out in accordance with 02.02 Laboratory Sample Preparation (TMECC 2001).

5.2.4 Sieve Analysis

Each 500 cm³ compost sub-sample was weighed and screened with nested sieves with openings of 9.5 mm, 6.3 mm, 4.0 mm, 2.0 mm, and 0.85 mm. Approximately half of each sub-sample was transferred to the top sieve each time, and the sieve shaker was set for 10 minutes. After sieving, the respective size fractions were placed into corresponding labeled and tared drying containers. An aliquot of 50 cm³ of each size fraction was taken and was oven dried at 70±5°C for 24-72 hours (until the sample weight change diminished to zero) to determine moisture content. Sample sieving and determination of moisture content were carried out in accordance with 02.02-B Sample Sieving for Aggregate Size Classification (TMECC 2001).

5.2.5 Analytical Methods

Feedstock and compost sub-samples were sent to a commercial lab (Norwest Labs, Edmonton) for trace metal analysis. At the lab, compost aliquots were prepared by removing inerts (such as glass and plastics) larger than 4 mm from bulk compost samples and grinding the compost to particles less than 2 mm in size. Test portions were digested in accordance with the extraction procedure described in US EPA Method 3050B Acid Digestion of Sediments, Sludges, and Soils (USEPA 1996). Arsenic, Cd, Co, Cr, Cu, Mo, Ni, Pb, Se and Zn content was determined using the US EPA Method 6020 Inductively

Coupled Plasma Mass Spectrometry (USEPA 1994a). Mercury content was determined in accordance with the procedure described in the US EPA Method 7471A Mercury in Solid and Semisolid Waste (Manual Cold-Vapor Technique) (USEPA 1994b).

Norwest Labs has received specific testing accreditations at an ISO 17025 standard. These accreditations are certified by the Standards Council of Canada on the recommendation of the Canadian Association of Environmental Analytical Laboratory and are recognized nationally and internationally. Norwest Labs has a stringent Quality Assurance Program monitoring the adherence to stated quality objectives and quality audit requirements. The quality control techniques used by the lab in analyzing the samples of this study included quality control check samples (standard reference materials), method blanks and duplicate analysis to check the accuracy of digestion and analysis.

5.2.6 Data Analysis

Single-factor (or one-way) Analysis of Variance (ANOVA) was used for analysis of trace metal concentrations in feedstocks or compost fractions of various particle sizes.

ANOVA assumes that randomly selected data values are from normally distributed populations and that the population variances, represented by the samples, are similar. ANOVA is robust and can tolerate some deviation from these assumptions, especially when sample sizes are equal (Montgomery 2001). These assumptions were checked before accepting the results. The advantage of using ANOVA rather than multiple t-tests is that doing so reduces the probability of a type-I error - rejecting the null hypothesis

when it is true (GURMSR 2006). Tukey's test was carried out to find out which materials were significantly different from each other. A significance level of 0.05 (confidence level = 0.95) was used in the ANOVA and Tukey tests.

5.3 Results and Discussion

The trace metal concentration analysis results for feedstock and compost samples are provided in Appendix E. Values reported as "< X" were regarded as half of "X" for data analysis and comparison.

5.3.1 Feedstock Materials from the MRF

Paper

Concentrations of As, Cd, Cr, Pb, Hg, Mo, Ni, Se, and Zn in three types of papers – paper with black ink, paper with coloured ink, and glossy paper with coloured ink – were similar. All concentrations for these elements were much lower than those for corresponding CCME Category A compost metal criteria. Concentrations for Co and Cu in the three types of papers were significantly different ($\alpha = 0.05$). The cobalt concentration in glossy paper with coloured ink was 2 mg kg^{-1} , an order of magnitude higher than in papers with black ink and coloured ink (Figure 5-3). The copper concentration in paper with coloured ink was the highest at 125 mg kg^{-1} . Paper with black ink contained the lowest Cu content, 1.0 mg kg^{-1} . Glossy paper with coloured ink contained 76.0 mg kg^{-1} of Cu. The concentrations for Co and Cu in the three types of papers were lower than those of the corresponding CCME Category A compost limits.

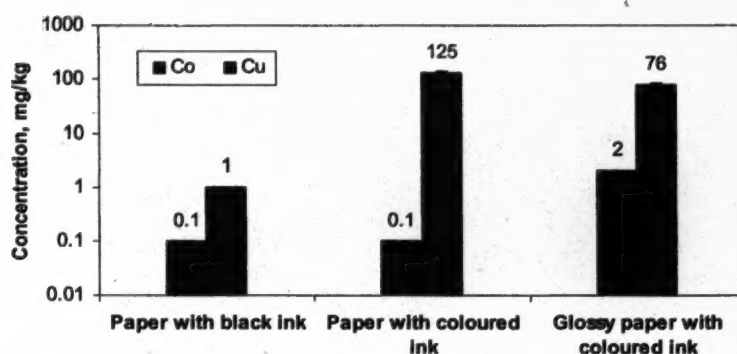


Figure 5-3. Co and Cu concentrations in different types of papers (Y bar: ± 1 standard error).

Coloured glossy paper contained higher Co content than black and coloured non-glossy papers, possibly due to the coating material – clay. Cobalt is one of the elements that is normally found in clay (IPCS INCHEM 2005; CEMC 2006). Coloured and coloured glossy papers had much higher Cu content than paper with black ink, probably because coloured ink is usually associated with Cu. Copper, as part of a copper phthalocyanine pigment, is normally used in blue and green inks (Tucker et al. 1999; About 2005).

Cardboard

ANOVA tests ($\alpha = 0.05$) indicated that differences in concentrations of As, Cd, Co, Cr, Pb, Hg, Mo, Ni, and Zn existed among three types of cardboards (cardboard printed on with black ink, cardboard printed on with coloured ink, and glossy cardboard printed on with coloured ink). No significant difference existed in Cu and Se concentrations among the three types of cardboards. Concentrations for As, Cd, Co, Hg, and Se in black ink, coloured ink, and glossy coloured ink cardboards were less than 1 mg kg^{-1} and were 100

times lower than those for the corresponding CCME Category A compost metal criteria. The concentrations for the other trace metals in the three types of cardboards are presented in Figure 5-4. Concentrations for Cu, Pb, Ni, Cr, and Zn in cardboard with coloured ink were less than those of the corresponding CCME Category A metal criteria. The molybdenum concentration in cardboard with coloured ink was 55.5 mg kg⁻¹, ten times higher than that of the CCME Category A Mo limit (5 mg kg⁻¹). Molybdenum is sometimes associated with orange pigments. Concentrations for Cu, Pb, Mo, Ni, Cr, and Zn in cardboard with coloured ink and glossy cardboard with coloured ink were less than those of the corresponding CCME Category A metal criteria.

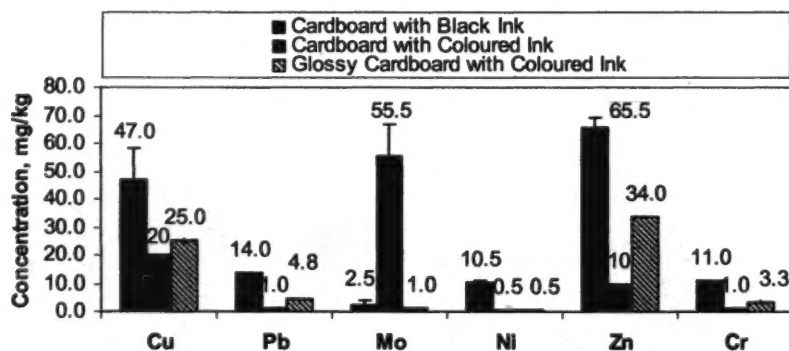


Figure 5-4. Cu, Pb, Mo, Ni, Zn and Cr concentrations in different types of cardboards (Y bar: ± 1 standard error).

It was found that concentrations for As, Cr, Pb, Hg, Ni, and Zn in black ink cardboard were significantly higher ($\alpha = 0.05$) than those in coloured ink and glossy coloured ink cardboards. This result was surprising in that coloured pigments contain trace metals, while black pigment (carbon black) contains essentially no trace metals (Chembytes e-zine 2006). One of the possible explanations for this is that a seemingly black colour might result from a combination of red, blue, and other colours. Thus, a seemingly black-

printed cardboard might contain trace metals from coloured pigments. Glossy coloured cardboard contained significantly higher ($\alpha = 0.05$) Co, Pb and Zn contents than coloured cardboard, possibly resulting from the clay coating on the surface of the glossy cardboard because clay can contain Co, Pb and Zn (IPCS INCHEM 2005).

Plastics

Concentrations for all trace metals except Cu in plastic with coloured ink were not significantly different from those in plastic without ink. Only the Cu concentration in plastic with coloured ink (10 mg kg^{-1}) was significantly higher ($\alpha = 0.05$) than that in plastic without coloured ink ($< 2 \text{ mg kg}^{-1}$). All trace metal concentrations in the two plastics were at least ten times lower than those of the corresponding CCME Category A criteria. It can be concluded that coloured images on the surface of plastic do not contribute significantly to trace metal contents in plastic. Plastic packaging items (plastic bags and rigid containers) are not likely to contribute significantly to metal concentrations in compost. Thus, plastic films and chips in composted materials are mainly of aesthetic concern rather than contributors of trace metals.

Glass

Glasses with brown, yellow, green and blue colours were sampled for trace metal analysis. Opal and red glasses were not found during sampling at the Edmonton Materials Recovery Facility perhaps because they are not widely used. Thus, opal and red glasses were not investigated. The analysis results indicated that the concentrations for 11 trace metals in the glass sample with brown and yellow colours (a mixture of brown and

yellow glasses) were exactly the same as those in the glass sample with blue and green colours (a mixture of blue and green glasses). The concentrations for Mo and Se in all the glass samples were one order of magnitude lower than those of the CCME Category A Mo and Se criteria. The concentrations for As, Cd, Cr, Co, Cu, Pb, Hg, Ni, and Zn in all samples were two to three orders of magnitude lower than those of the corresponding CCME Category A limits.

The literature on glass manufacturing suggests that different colours of glass result from different metallic oxides and that some glasses contain high trace metal concentrations, e.g., 1400 mg kg⁻¹ of Cr in green tinted glass. However, the analysis results of this study (obtained by using strong acid digestion without hydrofluoric acid) indicated that trace metal concentrations in glasses of different colours were the same. The Cr concentration in green tinted glass in this study was very low (less than 1 mg kg⁻¹). This inconsistency may be due to the fact that hydrofluoric acid was not used in digestion in this study. Trace metals in the glass matrix were probably not leached out in the digestion, and thus they were not detected in trace metal analysis. It may be concluded that trace metals in the glass matrix do not contribute significantly to the metal content in compost products.

5.3.2 Sorted Foreign Matter and Compost

Only one sample for each type of sorted foreign matter was analyzed for trace metal content due to the very small quantity of each material. The trace metal concentrations for each material are presented in Figure 5-5. Concentrations for all trace metals except Hg in sorted plastic and glass were lower than those in sorted metal and compost.

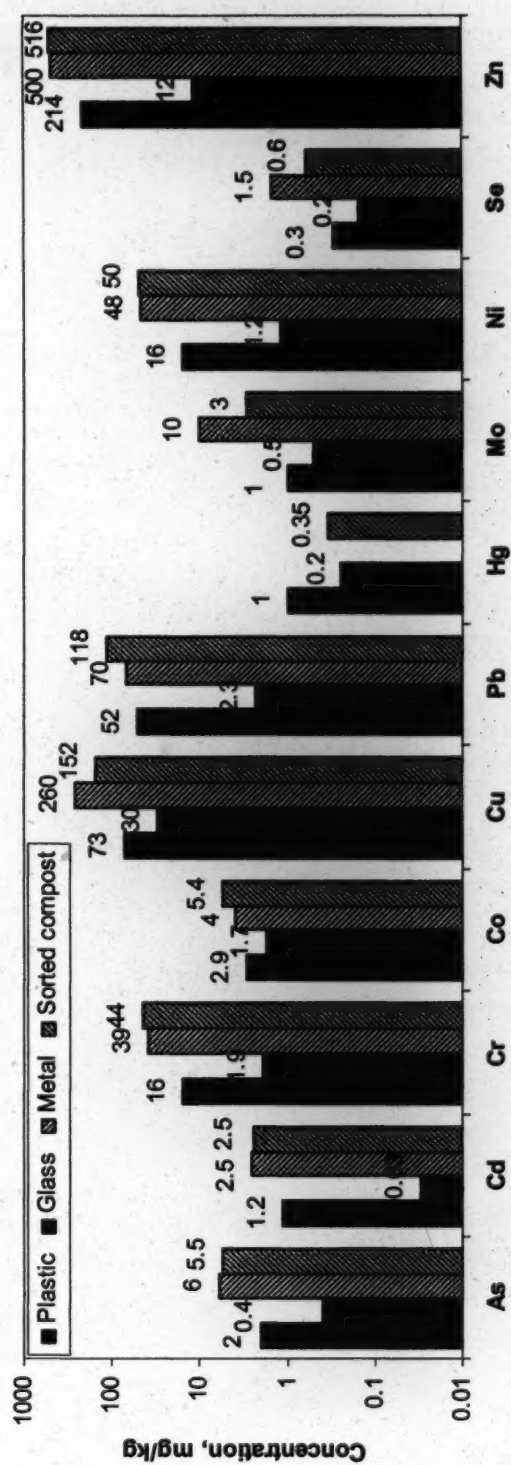


Figure 5-5. Trace metal concentrations in sorted foreign matter and compost (Hg concentration in metal foreign matter is not available).

The mercury concentration in sorted plastic was 1 mg kg^{-1} , higher than that in sorted glass and compost. All trace metal concentrations in sorted plastic were higher than those in sorted glass.

It was interesting to note that concentrations for As, Cu, Mo, and Se in sorted metal were not much higher than those in sorted compost. Concentrations for Cr, Co, Pb, Ni, and Zn in sorted metal were even lower than those in sorted compost. One of the possible reasons for this was that the so-called sorted metal consisted of not solely metals but a composite of metallic and non-metallic materials. Plastic and paper fiber were found adhering to metal materials. The non-metallic materials could result from composite materials used in packing and other consumer products such as aluminum-plastic material. In addition, some metals, including pure aluminum, might not contribute significantly to trace metal content. They might lower the trace metal content in sorted metal instead. Another possible reason may be incomplete digestion during trace metal analysis. Some metals (such as Cu and Zn in aluminum alloy) might not be completely solubilized during digestion and might remain in the solid portion, possibly lowering trace metal analysis results.

It can be seen from the above discussion that trace metal concentrations in compost can not be lowered by removing plastic and glass foreign matter from final compost products. Compost concentrations for Cu, Mo, and Se may be lowered by removing metal foreign matter from compost, but the removal of metal foreign matter may not help with compost concentrations for Cd, Cr, Co, Pb, Ni, and Zn.

Concentrations for As, Cd, Cr, Co, Cu, Pb, Hg, Ni, and Zn in plastic foreign matter were at least ten times higher than those in plastic from the MRF (Appendix E).

Concentrations for Cr, Co, Cu, Pb, Hg, Ni, and Zn in glass foreign matter were about ten times higher than those in glass from the MRF. Concentrations for As and Cd in glass foreign matter were slightly higher than those in glass from the MRF. Concentrations for Mo and Se in plastic and glass foreign matter were close to those in the plastic and glass from the MRF. One of the reasons for higher metal concentrations in plastic and glass foreign matter than in the plastic and glass from the MRF might be contamination of the materials during composting. It was observed during the study that plastic and glass foreign matter adsorbed fine composted materials on their surfaces. The fine composted materials contained relatively high metal concentrations, which could result in elevated metal concentrations in plastic and glass foreign matter. This contamination effect might be more significant for plastic because plastic is relatively light in weight and tends to adsorb more fines.

5.3.3 Sieved Compost Fractions

Sieve Analysis

Three unscreened cured MSW compost samples and two screened (passed through a 6.3 mm trommel screen) cured MSW compost samples were sieved using nested screens (with openings of 9.5 mm, 6.3 mm, 4.0 mm, 2.0 mm, and 0.85 mm) in the lab. The moisture content of each size fraction was tested. The raw data for the sieve analyses and the moisture content tests are provided in Appendix F, Tables F-1 and F-3. The dry

weight percentage, standard deviation, and relative standard deviation for each size fraction were calculated and are given in Appendix F.

The cumulative particle-size distributions for the unscreened and screened MSW compost samples are given in Figure 5-6. More than 99% of the screened compost sample was less than 6.3 mm in size; approximately 73% of the unscreened compost sample was less than 6.3 mm in size. Cumulative particle-size distribution curves for unscreened and screened MSW compost fractions of less than 6.3 mm are presented in Figure 5-7. The raw data for plotting the curves are provided in Appendix F, Tables F-2 and F-4. It can be seen from Figure 5-7 that small differences (about 7%) exist at particle sizes of 0.85 mm and 4.0 mm. The two cumulative particle-size distribution curves are, in general, similar.

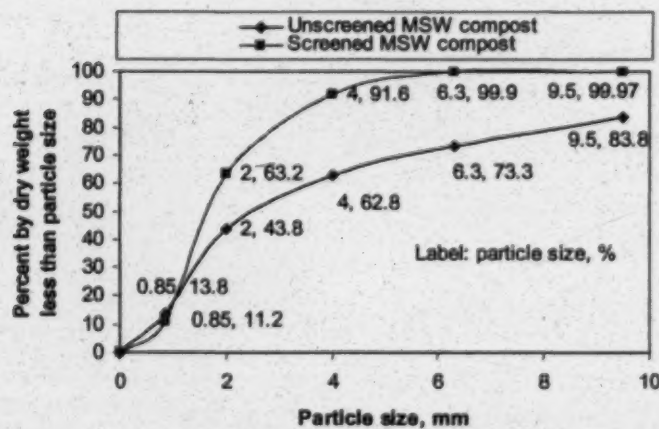


Figure 5-6. Cumulative particle-size distribution curves for unscreened and screened MSW compost samples (data are average dry weight percentages).

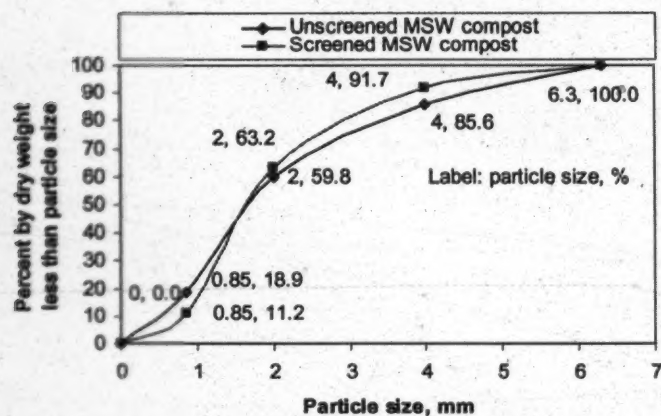


Figure 5-7. Cumulative particle-size distribution curves for unscreened and screened MSW compost fractions of less than 6.3 mm (data are average dry weight percentages).

Trace Metal Concentrations in Sieved Compost Fractions

Three compost fractions with particle sizes of 0 - 2.0 mm, 2.0 - 4.0 mm, and 4.0 - 6.3 mm from the sieve analysis of the screened compost sample were sent to a commercial lab for trace metal analysis. One compost fraction with particle sizes of larger than 6.3 mm from the sieve analysis of the unscreened compost sample was also analyzed for trace metal content. The analytical results are provided in Appendix E. The average trace metal concentrations for the four compost fractions of various particle sizes are compared in Figures 5-8 and 5-9.

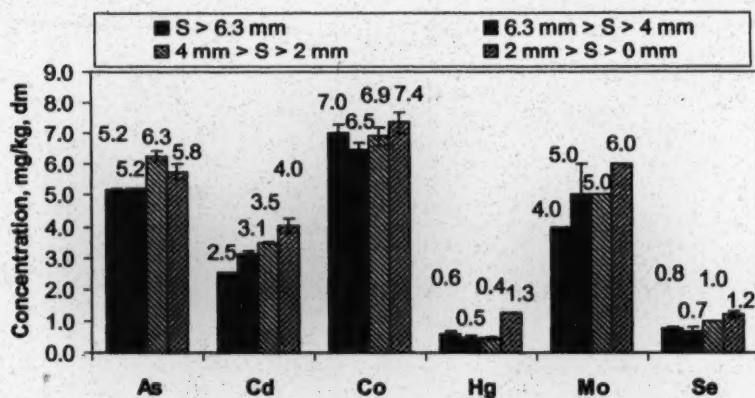


Figure 5-8. As, Cd, Co, Hg, Mo, and Se concentrations in sieved compost fractions of various particle sizes (Y bar: ± 1 standard error; S – particle size).

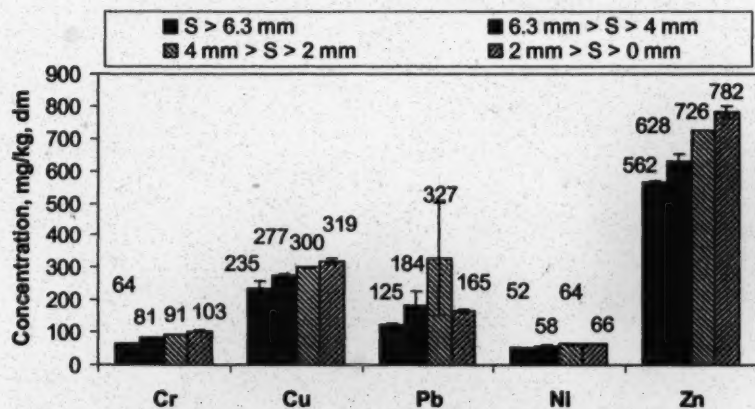


Figure 5-9. Cr, Cu, Pb, Ni, and Zn concentrations in sieved compost fractions of various particle sizes (Y bar: ± 1 standard error; S – particle size).

It can be observed from Figures 5-8 and 5-9 that trace metal concentrations tend to increase with a decrease in particle size. ANOVA analysis and Tukey tests ($\alpha = 0.05$) confirm the existence of the increasing trend of concentrations of As, Cd, Cr, Cu, Hg, Ni, Se, and Zn with a decrease in particle size. The increasing trend of Mo and Pb concentrations was not identified, possibly due to the large variations in the analysis results, as shown in Figures 5-8 and 5-9. A study on Guelph MSW compost (McCartney

2000) also revealed an increasing trend of Cu and Zn concentrations with a decrease in particle size ($\alpha = 0.1$), a result which is consistent with those of this study.

The coarse fraction of MSW compost (e.g., > 6.3 mm) was associated with foreign matter (such as plastic and glass) and stones, while the fine fraction of MSW compost was mostly compost. On the other hand, the coarse fraction contained relatively lower trace metal content, while the fine fraction contained relatively higher trace metal content. Conflict between foreign matter and trace metals occurred, i.e. the coarse fraction contained lower metal content but higher foreign matter content, while the fine fraction contained lower foreign matter content but higher metal content. Thus, it is difficult to produce a compost product satisfying both foreign matter and trace metal requirements by manipulating the particle size of compost.

5.4 Conclusions

- Concentrations for 11 trace metals in three types of papers (paper with black ink, paper with coloured ink, and glossy paper with coloured ink) were much lower than those of the corresponding CCME Category A compost trace metal criteria. Copper concentrations in coloured paper and coloured glossy paper (125 and 76 mg kg⁻¹, respectively) were much higher than that in paper with black ink (1 mg kg⁻¹ of Cu), probably because coloured ink is associated with Cu.
- Only the Mo concentration in cardboard with coloured ink, 55.5 mg kg⁻¹, exceeded the CCME Category A limit (5 mg kg⁻¹). The concentrations for the other trace metals in three types of cardboards (cardboard printed on with black

ink, cardboard printed on with coloured ink, and glossy cardboard printed on with coloured ink) were lower than those of the corresponding CCME Category A metal criteria.

- Concentrations for all the trace metals except Cu in plastic with coloured ink were not significantly different from those in plastic without ink. Only the Cu concentration in plastic with coloured ink (10 mg kg^{-1}) was significantly higher ($\alpha = 0.05$) than that in plastic without coloured ink ($< 2 \text{ mg kg}^{-1}$). All the concentrations for trace metals in the two plastics were at least ten times lower than those of the corresponding CCME Category A criteria. Coloured images on the surface of the plastic with coloured ink did not contribute significantly to trace metal content in the plastic.
- Concentrations for 11 trace metals in glass with brown and yellow colours were the same as those in glass with blue and green colours. Concentrations for As, Cd, Cr, Co, Cu, Pb, Hg, Mo, Ni, Se, and Zn in all the samples were much lower than those of the corresponding CCME Category A limits.
- Concentrations for As, Cd, Cr, Co, Cu, Pb, Hg, Ni, and Zn in plastic foreign matter were at least ten times higher than those in plastic from the MRF. Concentrations for Cr, Co, Cu, Pb, Hg, Ni, and Zn in glass foreign matter were about ten times higher than those in glass from the MRF. This finding might result from contamination of the materials during composting.
- The study indicates that concentrations of trace metals in compost may not be lowered by removing plastic and glass foreign matter from the compost.

- The coarse fraction of MSW compost contained lower trace metal content but higher foreign matter content, while the fine fraction contained lower foreign matter content but higher trace metal content. It is difficult to produce a compost product satisfying both foreign matter and trace metal requirements by manipulating the particle size of compost.

5.5 References

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Chapter 6 General Discussion and Conclusions

6.1 General Discussion

6.1.1 Beneficial Uses of Compost and Environmental Protection Standards

One of the attractive features of MSW composting is that a useful product – compost – can be produced through the composting of MSW. Compost is a soil amendment that can improve the physical conditions and fertility of soil. A number of macro-nutrients (e.g., N and P) and micro-nutrients (e.g., Cu and Zn) are added to soils through the application of compost. A buildup of trace metals in soils may occur after a prolonged use of compost. The excessive accumulation of trace metals (including micronutrients) can cause adverse effects on plants, animals, and humans (CCME 2005). For example, the excessive exposure to copper can result in liver and kidney damage (health risks posed by trace metals are summarized in Section 2.2). Thus, environmental protection standards for trace metals in compost are in place to protect humans and the environment.

Standards for trace metal concentrations in compost have been set in Canada-wide and provincial standards and guidelines. Trace metal content is an important factor that has been considered in classifying compost or assessing the quality of compost. Failure to meet the trace metal limits for the lowest compost classification means the compost can be regarded only as a waste and must be disposed of appropriately.

The application rate of compost has been established in the CFIA Trade Memorandum T-4-93 (CFIA 1997) under the *Fertilizers Act and Regulations*. The CFIA maximum

acceptable cumulative metal additions to soil over the long term are: As 15, Cd 4, Co 30, Hg 1, Mo 4, Ni 36, Pb 100, Se 2.8, and Zn 370 kg ha⁻¹. The term "long term" is taken to mean 45 years in the memorandum. Thus, annual maximum acceptable metal additions to soil should not exceed 1/45 of the long-term limits. These limits are somewhat restrictive to mixed MSW composters and end users of compost. For example, the MSW compost produced by the Edmonton Composting Facility (ECF) met the trace metal criteria for CCME Category B compost and the criteria in the CFIA Trade Memorandum T-4-93. The maximum allowable application rate of the ECF compost, which was approved by the CFIA in 2002, was up to 10 dry tonnes per hectare of cropland annually. However, studies have suggested that an application rate of more than 15 dry tonnes of MSW compost per hectare is needed to noticeably increase organic matter in soil and improve the physical properties of soil (Kirchhoff et al. 2002).

6.1.2 Trace Metal Reduction and Priority Trace Metals

It is important to identify the trace metals that deserve prior attention in designing the processes for trace metal reduction. The feedstock of mixed MSW composting consists of several categories of materials such as food scraps, biosolids, paper, cardboard, plastic, glass, leather, textiles, treated wood, metal, etc. These materials contain different types and levels of trace metals. The knowledge of priority trace metals is critical in order to focus on the manipulation of the feedstock materials that have the most significant impact on compost quality.

Priority trace metals were identified through a comparison of real-world trace metal concentration data to the CCME Category A compost standards. Historical data from the Edmonton Composting Facility (ECF) were used in this study. The ECF is a newly built mixed MSW composting plant, representing a new generation of composting plants. It is equipped with advanced technologies to improve compost quality. The ECF MSW compost met the CCME Category B compost standards for trace metals, but exceedances of the CCME Category A compost standards occurred. Based on the number and level of exceedances of the CCME Category A compost standards, the trace metals of concern, from the highest to lowest significance, were: Cd > Hg > Pb > Zn > As > Ni > Cu > Mo > Cr > Se. Cobalt was not of concern. The first three trace metals of high priority – Cd, Pb, and Hg – are the metals of no known value to either plants or animals (CCME 2005).

6.1.3 Trace Metal Reduction and Sources of Trace Metals

Understanding the sources of trace metals in mixed MSW compost systems is fundamental in designing contaminant reduction processes. Knowing the sources of trace metals will aid the selection of material separation technologies. Thus, identification of metal sources is a high-priority research area in trace metal reduction programs (Richard et al. 1993).

The review on trace metal sources indicated that noncompostables contributed to over 86% of the total content of As, Cd, Cr, Cu, Pb, Hg, Ni, and Zn in MSW (Section 4.4.10, Table 4-16). Product waste (resulting from the discarding of manufactured products and packing, mostly noncompostable) has increased dramatically in the past several decades

(Spiegelman and Sheehan 2006). The annual generation rate of the product waste in the U.S. increased from about 270 kg per capita in 1960 to over 560 kg per capita in 2000, but only 30% of the product waste was recycled in 2000 in the U.S. (Spiegelman and Sheehan 2006). The product waste that ends in the MSW stream can have an impact on the trace metal content in compost because metals are widely used in consumer products.

The review of the literature on product manufacturing and waste audits indicated that most manufactured products in the composting feedstock, including ferrous and non-ferrous materials, electrical and electronic products, batteries, treated wood, plastics, glass, paper, etc., could introduce trace metals into compost. Pure trace metals or their alloys are used in products such as aluminum and tin cans, electrical and electronic products, and batteries. Salts or oxides of trace metals are introduced to rubber, leather, textiles, glass, plastics, treated wood, etc. during the manufacturing of these products. Pure metal materials, such as copper wires, contain a high trace metal content and have the potential to contribute significantly to trace metal concentrations in compost. Some materials such as glass contain a relatively low trace metal content and may not contribute to the metal content in compost as much as pure metals.

The metal parts that are enclosed inside plastic shells of electronic products do not contact compost directly, but they may be soaked in leachate during composting. To what extent these metal parts contribute to the metal content in compost remains a question to be answered. For example, an earphone was found in the unscreened MSW compost product during a sampling program associated with this research (Section 5.1.1). The

earphone had gone through the whole composting process (about two years from mixing to curing). How much the earphone contributed copper to the compost is an interesting question because copper wires are normally used in earphones.

Fine materials including biosolids and dust may also contribute significantly to the trace metal content in compost. The review (in Sections 4.4.7 and 4.4.11) indicated that biosolids and household dust have a relatively high trace metal content. Biosolids can be a significant source of Cd, Co, Mo, Se, and Cr. The mass of household dust needs to be quantified, however, to determine whether or not the dust is a significant source of trace metals.

Besides feedstock materials, composting mixing drums were studied to determine the contribution of trace metals from the drums. The results indicated that composting mixing drums could contribute from 4.3% to 10.5% of the total Cu concentration in compost.

6.1.4 The Impact of Additives and Colourants on Trace Metal Content

Paper, cardboard, plastic, and glass materials of various types were sampled from the MRF to investigate the impact of additives and colourants on trace metal content. The results indicated that copper concentrations in coloured paper and coloured glossy paper (125 and 76 mg kg⁻¹ respectively) were much higher than that in paper with black ink (1 mg kg⁻¹), probably because coloured ink is associated with Cu. Concentrations for 11 trace metals in all the paper samples were much lower than those of the corresponding

CCME Category A compost trace metal criteria. Even if the mass reduction resulting from composting was considered, e.g. a mass loss of 50% which could lead to a concentration increase of 100%, the trace metals concentrations of composted materials were still lower than the CCME Category A criteria. The results suggest that paper is not likely a significant source of trace metals.

The concentrations for all the trace metals, except Mo, in three types of cardboards (cardboard printed on with black ink, cardboard printed on with coloured ink, and glossy cardboard printed on with coloured ink) were lower than those of the corresponding CCME Category A metal criteria. Even if the loss of mass of composted materials (such as a mass loss of 50%) was considered, trace metal concentrations except Mo in composted cardboard were still lower than the CCME Category A criteria. Only the Mo concentration in cardboard with coloured ink, 55.5 mg kg^{-1} , exceeded the CCME Category A limit (5 mg kg^{-1}). As the Mo concentration in coloured cardboard was more than ten times higher than the CCME limit, coloured cardboard may deserve attention in composting.

All the concentrations for trace metals in plastic and glass samples were much lower than those of the corresponding CCME Category A criteria. Coloured images on the surface of plastic did not contribute significantly to the trace metal content in the plastic. Common household glass containers that were sampled and analyzed in this study had a low trace metal content; thus, they were not considered a source of trace metals in compost systems.

6.1.5 Trace Metal Reduction after Curing

Plastic, glass, and metal foreign matter and compost fractions of various particle sizes were analyzed to investigate the possibility of trace metal reduction after curing. The results indicated that the concentrations for all the trace metals except Hg in the plastic and glass samples were lower than those in sorted compost (Section 5.2.3).

Concentrations for As, Cu, Mo, and Se in metal foreign matter were not much higher than those in sorted compost. Concentrations for Cr, Co, Pb, Ni, and Zn in metal foreign matter were even lower than those in sorted compost. This finding suggested that separating foreign matter from compost after curing would not be an appropriate way to reduce the trace metal content in compost.

The analysis of compost fractions of various particle sizes indicated that the coarse fraction of MSW compost contained lower trace metal content but higher foreign matter content, while the fine fraction contained lower foreign matter content but higher trace metal content. It would be difficult to produce a compost product satisfying both foreign matter and trace metal requirements by manipulating the particle size of compost.

6.2 Conclusions

- The CFIA maximum acceptable cumulative metal additions to soil are restrictive for mixed MSW composters. The compost standards challenge MSW composters to reduce the trace metal content in compost.
- The knowledge of priority trace metals is important in selecting separation technologies to achieve the goal of trace metal reduction. Based on the number

and level of exceedances of the CCME Category A compost standards, the trace metals of concern, from the highest to lowest significance, were: Cd > Hg > Pb > Zn > As > Ni > Cu > Mo > Cr > Se.

- Identification of metal sources is a high priority research area in metal contaminant reduction programs. Noncompostables contributed to over 86% of the total content of As, Cd, Cr, Cu, Pb, Hg, Ni, and Zn in MSW. The products that contain pure trace metals or their alloys, such as electrical and electronic products, have the potential to contribute significantly to trace metal concentrations in compost. The products containing a relatively low trace metal content, such as rubber, leather, textiles, glass, and plastics, may not contribute to the metal content in compost as much as pure-metal items.
- Biosolids and household dust have a relatively high trace metal content. Biosolids can be a significant source of Cd, Co, Mo, Se, and Cr. The mass of household dust needs to be quantified to determine whether or not dust is a significant source of metals.
- Concentrations for 11 trace metals in all the paper samples were much lower than the corresponding CCME Category A compost trace metal criteria. Paper is not likely to be a source of trace metals. The Mo concentration in cardboard with coloured ink, 55.5 mg kg^{-1} , was much higher than the CCME Category A limit (5 mg kg^{-1}). All the concentrations for trace metals in plastic and glass samples were much lower than the CCME Category A criteria. Coloured images printed on plastic did not contribute significantly to trace metal content in the plastic.

Common household glass containers that were sampled and analyzed in this study were not considered a source of trace metals in compost systems.

- Concentrations for all trace metals except Hg in the plastic and glass samples were lower than those in sorted compost. Concentrations for As, Cu, Mo, and Se in metal foreign matter were not much higher than those in sorted compost. Concentrations for Cr, Co, Pb, Ni, and Zn in metal foreign matter were even lower than those in sorted compost. This finding suggested that separating foreign matter from compost after curing would not be an appropriate way to reduce trace metal content in compost.
- The coarse fraction of MSW compost contained lower trace metal content but higher foreign matter content, while the fine fraction contained lower foreign matter content but higher trace metal content. It would be difficult to produce a compost product satisfying both foreign matter and trace metal requirements by manipulating the particle size of compost.

6.3 Recommendations for Future Work

- There is the potential for metal contributions to be added to compost from mechanical handling systems. The investigation on the metal contribution from composting mixing drums revealed that the mixing drums could contribute from 4.3% to 10.5% of the total Cu content in compost (Section 4.4.12). The contributions of trace metals from other processing machines, such as screens and turners, were not investigated. Thus, the overall contribution of trace metals from

processing equipment is an interesting question. There may be a need for further investigation on the metal contributions from other processing machines.

- Some electrical and electronic products contain an extremely high trace metal content (e.g., pure Cu), but the trace metals contained in these products may not completely get into compost. Some of the products are removed from composting systems at separation stages; some of them will remain in compost. It is important to understand the trace metal leachabilities from these products at different stages of the composting process to determine when these products have to be removed from the composting system to avoid serious contamination. Studies need to be carried out to investigate the leachabilities of trace metals from electrical and electronic products that are commonly found in MSW.
- Dewatered biosolids (typically having a solid content of about 25%) is used in MSW and biosolids co-composting primarily to achieve desired moisture content of the composting material. The literature review indicated that biosolids could be a significant source of Cd, Co, Mo, Se, and Cr. Thus, there is a need for balancing composting process requirements and compost trace metal content. It may be necessary to carry out an experiment with and without using biosolids as composting feedstock to investigate the impact of biosolids on trace metal levels in MSW compost. The proposed experiment can help determine whether or not biosolids should be used in MSW composting.
- Household dust contains high Pb, Cd, and Hg contents. The mass of household dust should be investigated to determine whether or not household dust is a significant source of trace metals.

6.4 References

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7 Appendices

Appendix A Cumulative Frequency Distribution Plots for Trace Metals in Edmonton MSW Compost

In the following plots, "long dash" lines indicate CCME standard limits, and "short dash" lines indicate medians.

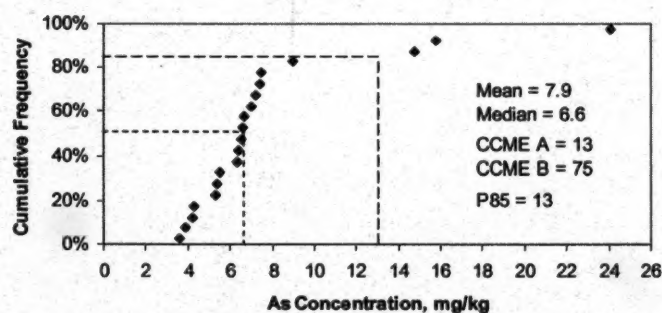


Figure A-1. Cumulative frequency distribution plot for As concentration (P85 indicates probability of compliance with CCME Category A limit is 85%).

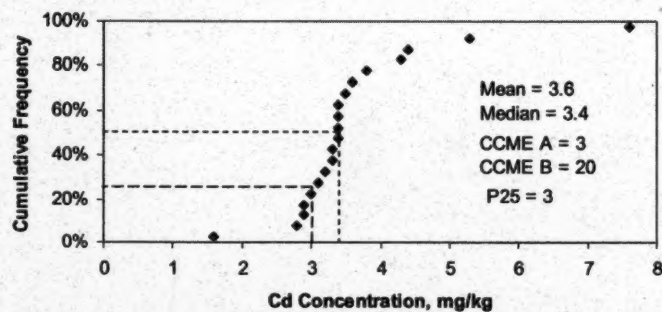


Figure A-2. Cumulative frequency distribution plot for Cd concentration (P25 indicates probability of compliance with CCME Category A limit is 25%).

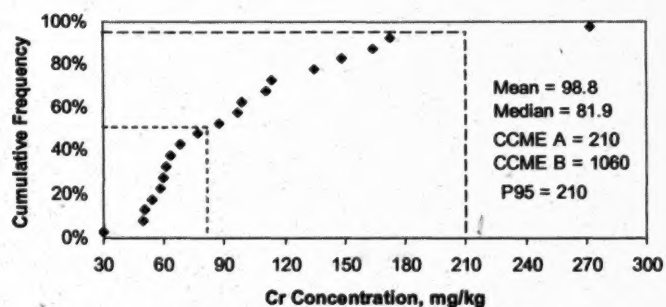


Figure A-3. Cumulative frequency distribution plot for Cr concentration (P95 indicates probability of compliance with CCME Category A limit is 95%).

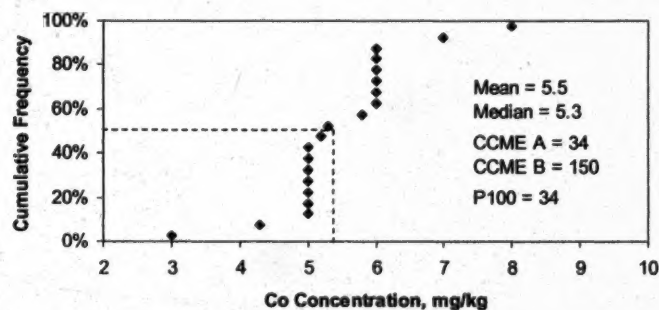


Figure A-4. Cumulative frequency distribution plot for Co concentration (P100 indicates probability of compliance with CCME Category A limit is 100%).

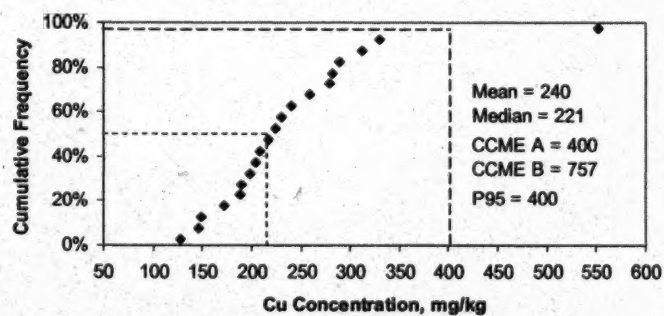


Figure A-5. Cumulative frequency distribution plot for Cu concentration (P95 indicates probability of compliance with CCME Category A limit is 95%).

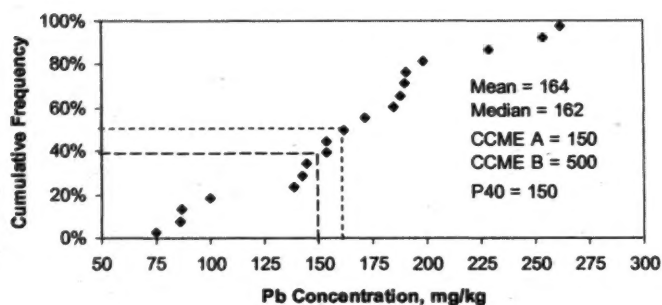


Figure A-6. Cumulative frequency distribution plot for Pb concentration (P40 indicates probability of compliance with CCME Category A limit is 40%).

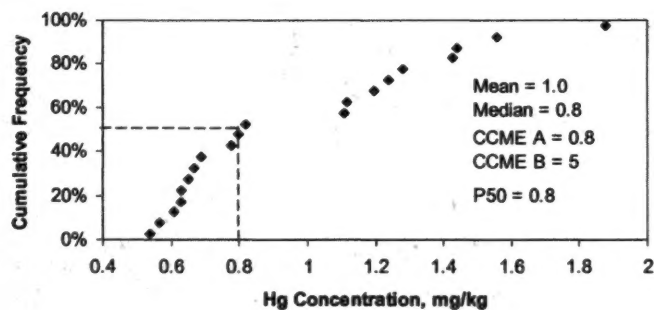


Figure A-7. Cumulative frequency distribution plot for Hg concentration (P50 indicates probability of compliance with CCME Category A limit is 50%).

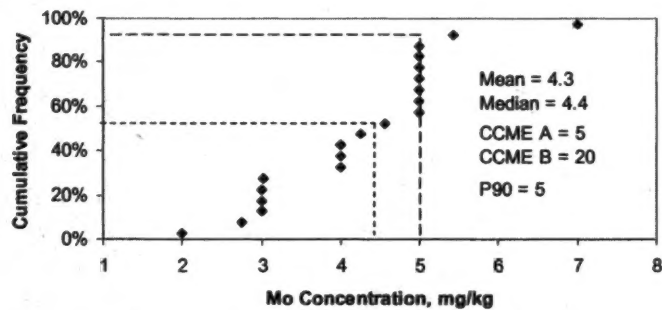


Figure A-8. Cumulative frequency distribution plot for Mo concentration (P90 indicates probability of compliance with CCME Category A limit is 90%).

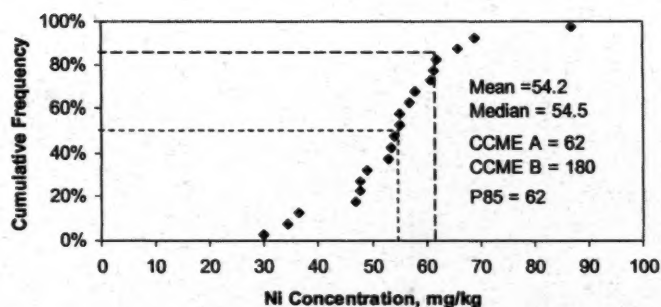


Figure A-9. Cumulative frequency distribution plot for Ni concentration (P85 indicates probability of compliance with CCME Category A limit is 85%).

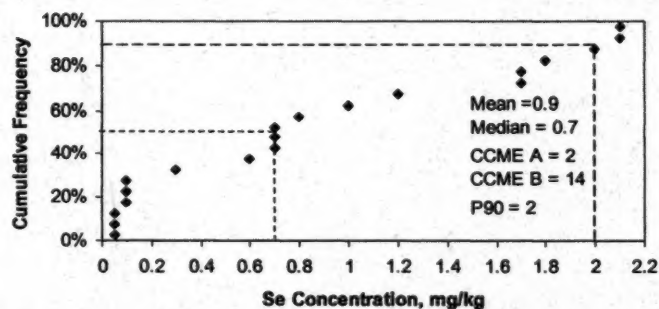


Figure A-10. Cumulative frequency distribution plot for Se concentration (P90 indicates probability of compliance with CCME Category A limit is 90%).

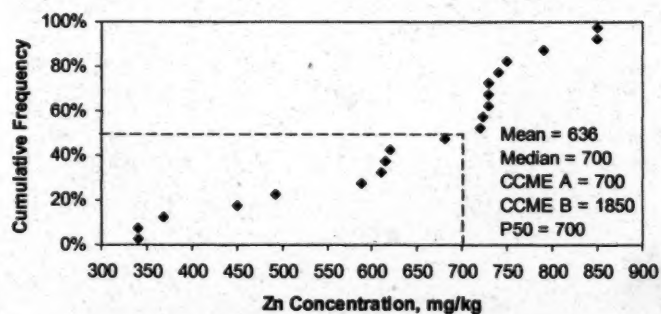


Figure A-11. Cumulative frequency distribution plot for Zn concentration (P50 indicates probability of compliance with CCME Category A limit is 50%).

Appendix B Trace Metal Concentration Temporal Trend

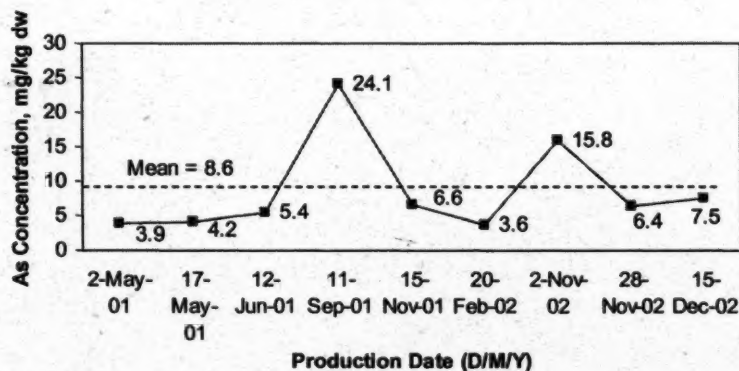


Figure B-1. Edmonton MSW compost As concentration temporal trend.

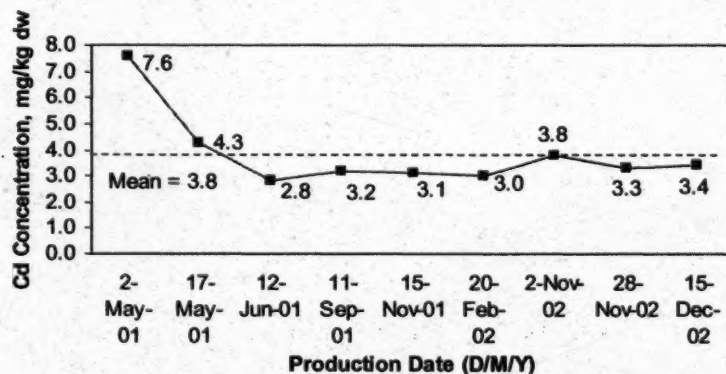


Figure B-2. Edmonton MSW compost Cd concentration temporal trend.

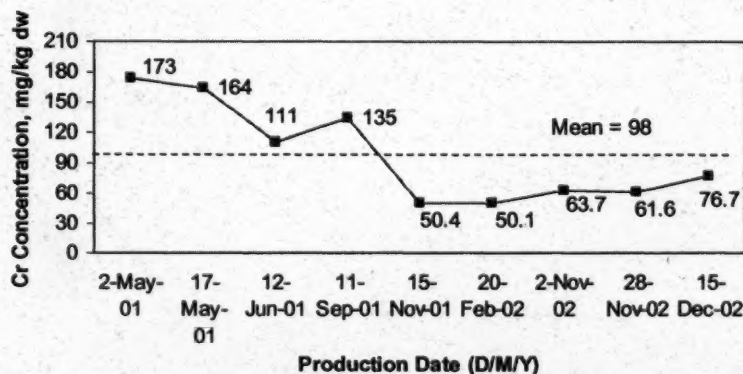


Figure B-3. Edmonton MSW compost Cr concentration temporal trend.

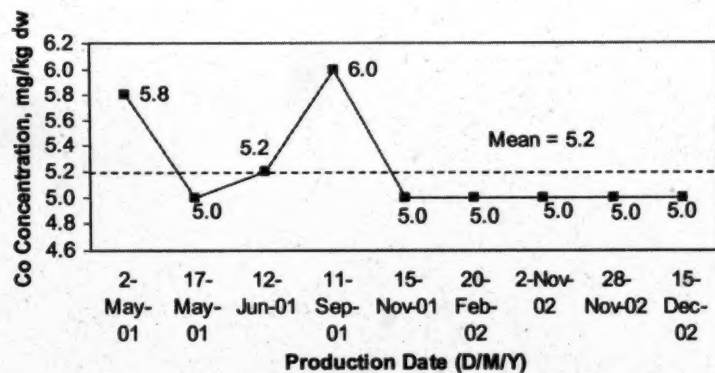


Figure B-4. Edmonton MSW compost Co concentration temporal trend.

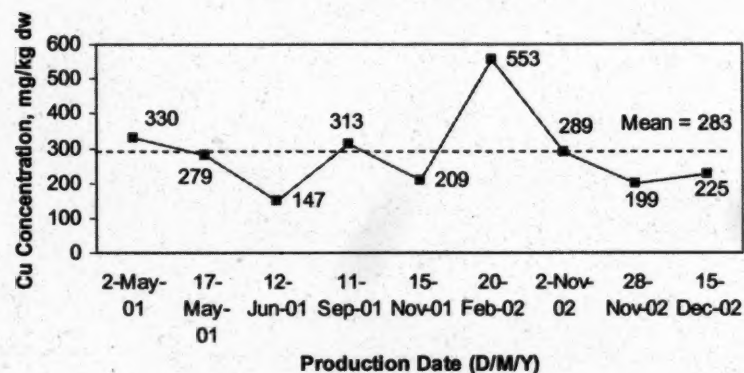


Figure B-5. Edmonton MSW compost Cu concentration temporal trend.

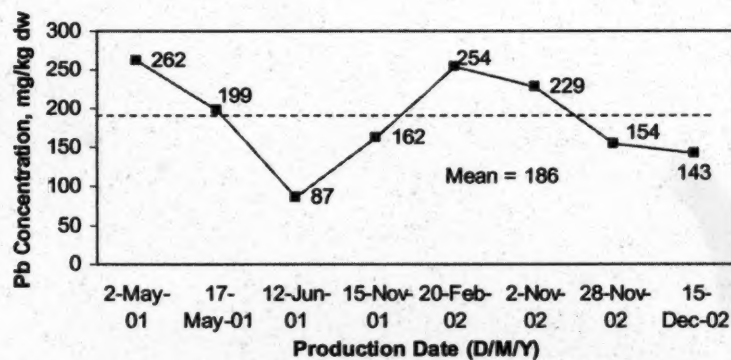


Figure B-6. Edmonton MSW compost Pb concentration temporal trend.

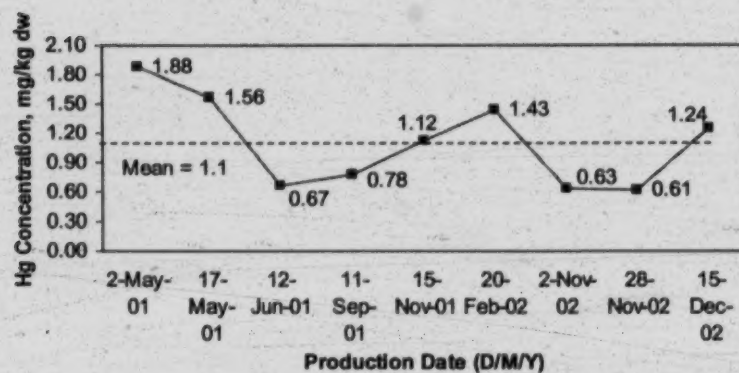


Figure B-7. Edmonton MSW compost Hg concentration temporal trend.

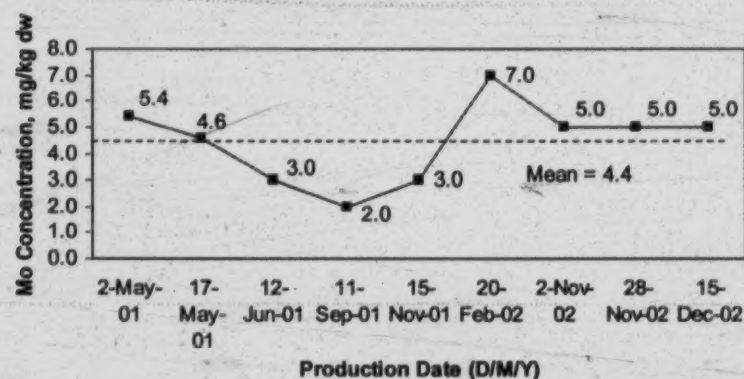


Figure B-8. Edmonton MSW compost Mo concentration temporal trend.

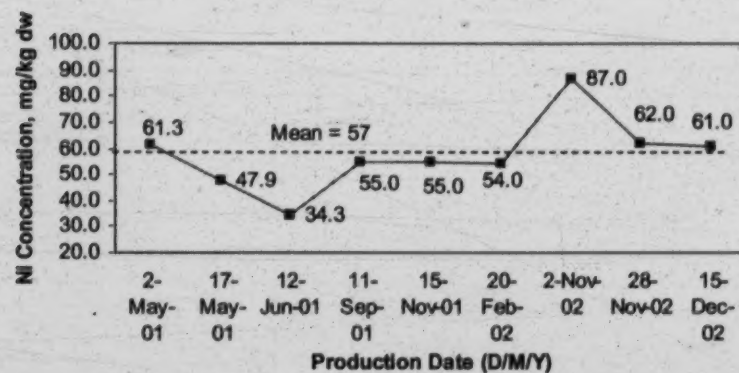


Figure B-9. Edmonton MSW compost Ni concentration temporal trend.

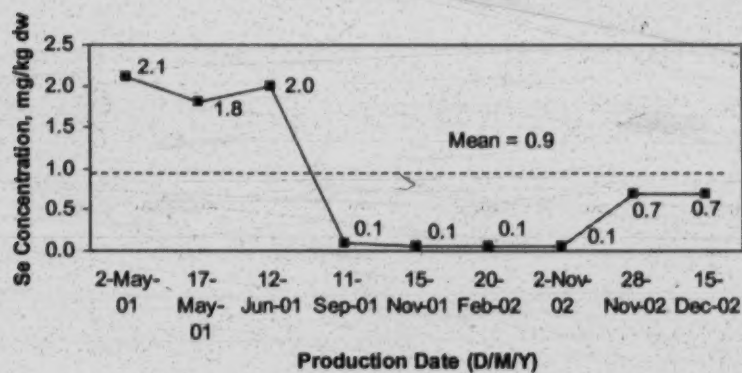


Figure B-10. Edmonton MSW compost Se concentration temporal trend.

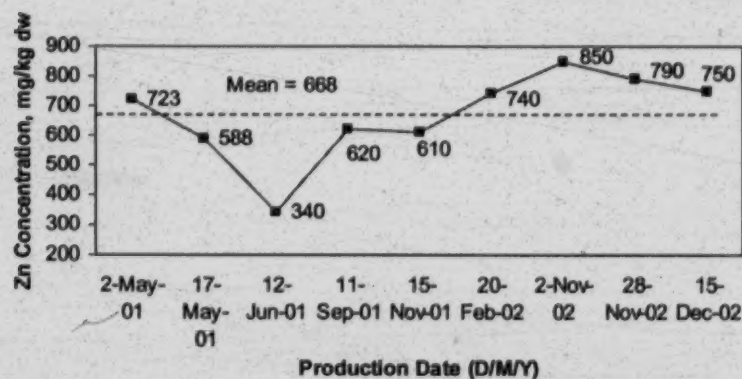


Figure B-11. Edmonton MSW compost Zn concentration temporal trend.

Appendix C The Contribution of Mixing Drum Lining to Compost Metal Content

The contribution of the mixing drum's metal lining to compost trace metal content was calculated as follows:

Data Used in the Calculation

- Mixing drum metal loss each year: 1.59 mm (Latta 2005)
- Mixing drum: Inside diameter (D) 4.9 m (16 feet); length (L) 64 m (210 feet); 5 drums (Yee 2005)
- Mixing drum liner: ASTM A 36 carbon structural steel (Yee 2005)
- Carbon steel composition (EFOUND A 2005):

Carbon steels are steels whose alloying elements do not exceed the limits in Table C-1:

Table C-1. Carbon steel alloying element content.

Element	Max weight, %
C	1.00
Cu	0.60
Mn	1.65
P	0.40
Si	0.60
S	0.05

ASTM A 36 carbon structural steel chemical requirements are listed in Table C-2 (ASTM 2004):

Table C-2. ASTM A 36 carbon structural steel chemical requirements (selected shapes).

Element	All shapes	Plates (to 20 mm)	Plates (20 -40 mm)	Plates (40-65 mm)
C, max, %	0.26	0.25	0.25	0.26
Cu, min, % when copper steel is specified	0.20	0.20	0.20	0.20
Mn, %	No requirement	No requirement	0.80-1.20	0.80-1.20
P, max, %	0.04	0.04	0.04	0.04
Si, %	0.4 max	0.4 max	0.4 max	0.15-0.40
S, max, %	0.05	0.05	0.05	0.05

According to ASTM (2004), ASTM A 36 carbon structural steel contains >0.20% Cu when copper steel is specified, but the Cu content should be less than 0.60% based on EFOUNDA (2005). Thus, Cu content 0.60% is used in the calculation of drum liner contribution considering the worst case scenario.

- Plain carbon steel density: 7.86 tonne/m³ (Elert 2005)
- Uncured compost produced (City of Edmonton 2004; City of Edmonton 2005):
45894 wet tonnes (29831 dry tonnes) in 2003;
26395 wet tonnes (17157 dry tonnes) in 2004

Assume moisture content of uncured compost is 35% based on 2001 Annual Report (City of Edmonton 2002).

Calculation of Mixing Drum Contribution to Compost Metal Content

- Volume (V) of steel loss for each drum per year

$$\begin{aligned}
 V &= \text{area} \times \text{length} = \pi D \times 1.59 \text{ mm} \times 10^{-3} \text{ m/mm} \times L \\
 &= 3.14 \times 4.9 \text{ m} \times 1.59 \text{ mm} \times 10^{-3} \text{ m/mm} \times 64 \text{ m} \\
 &= 1.57 \text{ m}^3
 \end{aligned}$$

- Total volume of steel loss for five drums

$$V_{\text{tot}} = 1.57 \text{ m}^3 \times 5 = 7.83 \text{ m}^3$$

- Mass of carbon steel loss of five drums

$$V_{\text{tot}} \times \text{Density} = 7.83 \text{ m}^3 \times 7.86 \text{ tonne/m}^3 = 61.52 \text{ tonnes}$$

- Cu mass in the lost carbon steel

Assume the mixing drum carbon steel contains 0.60% Cu.

$$\text{Cu mass: } 61.52 \text{ tonnes} \times 0.60\% = 0.37 \text{ tonnes}$$

- Contribution to uncured compost metal content

Assume the Cu loss completely gets into uncured compost.

Cu contribution from drum:

29831 dry tonnes compost in 2003

$$0.37 \text{ tonnes} / 29831 \text{ tonnes} = 0.0012\% = 12 \text{ mg kg}^{-1}$$

17157 dry tonnes compost in 2004

$$0.37 \text{ tonnes} / 17157 \text{ tonnes} = 0.0022\% = 22 \text{ mg kg}^{-1}$$

Proportion of Mixing Drum Contribution to Final Compost Product Concentration

The percentage of the mixing drum contribution accounting for the final compost metal concentration was calculated and summarized in Table C-3. The percentages for 2003 and 2004 are 4.3% and 10.5%, respectively. The percentage value for 2004 is more than two times larger than that for 2003 because the reported compost productions for 2003 and 2004 (45894 and 26395 wet tonnes respectively) varied largely.

Table C-3. Proportion of mixing drum contribution to final compost concentration.

Year	Metal	Final Compost Product Conc. (mg kg ⁻¹) ¹	Contribution from Drum Metal Loss (mg kg ⁻¹)	Proportion of Contribution from Drum to Final Compost ²
2003	Cu	277	12	4.3%
2004	Cu	209	22	10.5%

¹ Cured compost metal concentration (City of Edmonton 2004; City of Edmonton 2005).

² Proportion of Contribution from Drum to Final Compost = Contribution from Drum Metal Loss (mg kg⁻¹) / Final Compost Product Conc. (mg kg⁻¹) × 100%.

Appendix D The Calculation for Developing Trace Metal Mass Flow Diagram

Composting Feedstocks and Outputs at the Edmonton Composting Facility (ECF)

The feedstocks received at the Edmonton Composting Facility (ECF) are municipal solid waste (MSW) from residential sources and biosolids (City of Edmonton 2005).

Residential waste consists of the most part of the ECF feedstock. The residential waste composition audit result (excluding recyclables) is presented in Table D-1 (Schubert and Gannon 2001). The biosolids feedstock used at the ECF is from Clover Bar lagoon in summer or from Gold Bar wastewater treatment plant in winter.

TableD-1. Single and multi family residential waste composition.

Waste Component	Residential ¹ (%)
Food	23.3
Other Organics	9.0
Paper	16.5
Yard Waste	28.9
Metal	2.6
Aluminum	0.6
Plastics	7.1
Glass	2.1
Textiles	2.8
Other Waste	6.0
HHW	1.0
Total	100

HHW: Household hazardous waste.

¹ Residential (single and multi-family) waste composition annual results (Schubert and Gannon 2001). This residential waste sort result excluded recyclables.

The outputs of the ECF include tip floor discards, tip recovered materials, primary residuals, secondary residuals, recovered metals, cure pad residuals and compost. The annual quantities of the materials except compost are summarized in Table D-2.

Table D-2. ECF annual quantities.

	MSW Stream	Tonnage ¹	Moisture, %	Dry tonnage	MSW stream to MSW received ratio ⁴ (dry weight)
Inputs	Bio-solids, dry tonnes	14379	NA	14739	0.17
	MSW Received, tonnes	146252	42% ²	84826	1.00
Outputs	Tip Floor Discards, tonnes	20110	NA	NA	NA
	Tip Floor Recov'd, tonnes	369.7	NA	NA	NA
	Metals Recov'd, tonnes	1082	NA	NA	NA
	Primary Resid, tonnes	32628	38% ³	20229	0.24
	Secondary Resid. tonnes	26289	28% ³	18928	0.22
	Cure Pad Resid, tonnes	1155	NA	NA	NA

¹ ECF 2004 quantities (City of Edmonton 2005).

² Calculated based on Edmonton MSW composition and Tchobanoglous et al (1993). See Table D-3 for details.

³ Moisture content from Edmonton Waste audit results (Schubert 2005).

⁴ MSW stream to MSW received ratio = dry weight of the component/MSW received (dry tonnes).

NA - Not available.

The moisture content in Table D-2 were calculated based on Edmonton residential MSW composition (Schubert and Gannon 2001) and the moisture content of typical residential MSW (Tchobanoglous et al. 1993). The moisture contents for different waste component are summarized in Table D-3. Estimated City of Edmonton residential MSW (as received) moisture content is 42%. The MSW stream to MSW received ratio (dry weight basis) was also calculated and presented in Table D-3. This ratio was used to determine the dry weight of biosolids (6630 tonnes), primary residuals (9360 tonnes) and secondary residuals (8580 tonnes) in the condition of 93000 tonnes of dry MSW.

In 2002, 2003 and 2004, uncured compost produced were 68666, 45894, and 26395 wet tonnes, respectively; MSW received were 167212, 141884, and 146252 wet tonnes, respectively (City of Edmonton 2003; City of Edmonton 2004; City of Edmonton 2005). The average compost produced to MSW received ratio for the three years is 0.34 based on moisture contents of 42% for MSW and 33% for compost. The waste audit of 2001 indicated the compost moisture content is 33% (Schubert 2005).

Table D-3. Estimated ECF residential MSW moisture content.

Component	% wet weight ¹	Moisture content ² , %
Food Waste	23	70
Yard Waste	29	60
Other Organics	9	NA
Paper & Cardboard	17	6
Metal & Aluminum	3	2
Glass	2	2
Plastic	7	2
Textiles	3	10
Other Waste	7	NA
Total	100	42

¹ Data source: Schubert and Gannon (2001).

² Data source: Tchobanoglous et al (1993).

NA – Not available.

Metal Concentration Data Used in the ECF Mass Flows Diagram

Metal Concentration Data from the ECF

- Biosolids concentration data are from the analysis of Nutri-Gold composite samples for 2001-2004 (Table D-4). The average of the four years was used in mass balance calculation.
- The average uncured compost metal concentration for 2000 and 2001 (TransAlta 2001; City of Edmonton 2002) was used in calculation.

Metal Concentrations Calculated based on ECF Waste Audit Results and Literature

- Primary residuals metal concentrations were calculated based on the composition of primary residuals (Table D-5) and the metal concentration results for waste components from U.S. Cape May County MSW characterization study (Rugg and Hanna 1992). Moisture data for different waste components (Tchobanoglous et al 1993), average primary residual moisture (Schubert 2005), and uncured compost metal concentrations (TransAlta Energy 2001; City of Edmonton 2002) were also used in the calculation. The calculation results were summarized in Table D-6.
- Secondary residuals metal concentrations were calculated based on the composition of primary residuals (Table D-5) and the metal concentration results for waste components from U.S. Cape May County MSW characterization study (Rugg and Hanna 1992). Moisture data for different waste components (Tchobanoglous et al 1993), average primary residual moisture (Schubert 2005), and uncured compost metal concentrations (TransAlta 2001; City of Edmonton 2002) were also used in the calculation. The calculation results were summarized in Table D-7.

Table D-4. Clover Bar biosolids metal content, mg kg⁻¹ dry mass (Bittner 2005).

Metal	As	Cd	Co	Cr	Cu	Hg	Mo	Ni	Pb	Se	Zn
2001	6	7.2	9.4	438	264	1.2	4.9	50.5	126	ND	547
2002	5.3	7.5	16.6	322	376	1.5	7.7	56.2	104	ND	757
2003	5.0	8.4	20.7	183	536	1.6	9.2	70.3	97	2.5	868
2004	4.2	5.6	15.6	104	540	1.1	9.0	46.8	71	3.0	692
Mean	5.1	7.2	15.6	262	429	1.4	7.7	56.0	100	1.9	716
Standard											
Deviation	0.7	1.2	4.7	148.1	133.9	0.2	2.0	10.3	22.7	1.0	134.1
%RSD	14.6	16.2	29.9	56.5	31.2	17.0	25.7	18.4	22.7	54.3	18.7
Detection											
limit	0.5	4	4	60	60	0.01	5	7	40	2	40

Note: ND - Not detected. Value is below the Minimum Detectable Limit (MDL).

Mean: four-year arithmetic average except for Se (two-year). Values below MDL were regarded as half of MDL in calculation.

Table D-5. ECF Primary and Secondary Residual Compositions (Schubert and Gannon 2001).

Waste component	Primary residual, % by weight, average	Secondary residual, % by weight, average
Textiles	21.80	4.90
Film plastic	25.05	8.70
Rigid plastic	19.12	13.93
Ferrous metal	15.95	2.67
Compost	5.89	33.11
Wood	5.74	1.87
Rubber	2.20	0.14
Paper	1.87	16.47
Non-ferrous	1.40	2.28
Foam	0.42	0.54
Rock/Concrete	0.52	0.97
Glass	0.04	9.30
Bone	NA	1.58
Batteries	NA	0.93
Ceramic	NA	2.62
Total	100.00	100.00

NA - Not available.

Table D-6. Estimated ECF primary residual metal concentrations.

Waste component	Primary residual ³ , % by weight	Moisture ¹ , %	Dry weight, kg	As ⁴ mg kg ⁻¹	Cd ⁴ mg kg ⁻¹	Co ⁴ mg kg ⁻¹	Cu ⁴ mg kg ⁻¹	Pb ⁴ mg kg ⁻¹	Hg ⁴ mg kg ⁻¹	Mo ⁴ mg kg ⁻¹	Ni ⁴ mg kg ⁻¹	Se ⁴ mg kg ⁻¹	Zn ⁴ mg kg ⁻¹
Textiles	21.80	55.1	9.8	1.0	23.0	469.0	NA	30.0	58.0	0.3	NA	NA	806
Film plastic	25.05	11.0	22.3	0.6	6.0	100.0	NA	31.0	565	0.2	NA	NA	151
Rigid plastic	19.12	11.0	17.0	0.2	ND	8.0	NA	10.0	23.0	0.1	NA	NA	83.0
Ferrous metal	15.95	5.0	15.2	11.4	14.0	4500	NA	157	163	0.7	NA	NA	1100
Compost	5.89	50.0	2.9	5.2 ⁵	3.3 ⁵	89 ⁵	4.5 ⁵	205 ⁵	146 ⁵	1.0 ⁵	3.5 ⁵	1.1 ⁵	599 ⁵
Wood	5.74	50.0	2.9	40.3	ND	62.0	NA	38.0	129	2.6	NA	NA	246
Rubber	2.20	11.0	2.0	1.0	23.0	469.0	NA	30.0	58.0	0.3	NA	NA	806
Paper	1.87	70.0	0.6	0.6	ND	7.0	NA	79.0	14.0	0.1	NA	NA	88.0
Non-ferrous	1.40	16.5	1.2	0.3	12.0	65.0	NA	6494	1050	ND	NA	NA	830
Foam	0.42	38 ²	0.3	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Rock/Concrete	0.52	2.9	0.5	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Glass	0.04	0.2	0.0	ND	ND	ND	NA	ND	84.0	0.2	NA	NA	ND
Bone	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Batteries	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Ceramic	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Total	100.00		74.6	4.5	8.6	1027	NA	167	244	0.4	NA	70.6	461

¹ Adjusted Tchobanoglous et al (1993) residential MSW data by using average primary residual moisture 38% (Schubert 2005).² Average of 10 samples, 2002 ECF waste audit data (Schubert 2005).³ Schubert and Gannon (2001).⁴ Rugg and Hanna (1992) unless cited. ND - Not detected. Rugg and Hanna (1992) reported zero was used to substitute ND in calculations and detection limits were not reported.⁵ Concentrations are 2000 and 2001 average for uncured compost from First (TransAlta 2001) and 2001 (City of Edmonton 2002) Annual Reports.

Note: NA - No available. The waste component corresponding to NA was not included in metal concentration calculation.

Table D-7. Estimated ECF secondary residual metal concentrations.

Waste component	Secondary residual ³ , % by weight	Moisture ¹ , %	Dry weight, kg	As ⁴ , mg kg ⁻¹	Cd ⁴ , mg kg ⁻¹	Cr ⁴ , mg kg ⁻¹	Co, mg kg ⁻¹	Cu ⁴ , mg kg ⁻¹	Pb ⁴ , mg kg ⁻¹	Hg ⁴ , mg kg ⁻¹	Mo, mg kg ⁻¹	Ni ⁴ , mg kg ⁻¹	Se, mg kg ⁻¹	Zn ⁴ , mg kg ⁻¹
Textiles	4.90	40.6	13.0	1.0	23.0	469.0	NA	30.0	58.0	0.3	NA	6.0	NA	806
Film plastic	8.70	8.1	23.0	0.6	6.0	100.0	NA	31.0	565	0.2	NA	ND	NA	151
Rigid plastic	13.93	8.1	17.6	0.2	ND	8.0	NA	10.0	23.0	0.1	NA	ND	NA	83.0
Ferrous metal	2.67	12.2	14.0	11.4	14.0	4500	NA	157	163	0.7	NA	320	NA	1100
Compost	33.11	45.0	3.2	5.2 ⁵	3.3 ⁵	89 ⁵	4.5 ⁵	205 ⁵	146 ⁵	1.0 ⁵	3.5 ⁵	47 ⁵	1.1 ⁵	599 ⁵
Wood	1.87	45.0	3.2	40.3	ND	62.0	NA	38.0	129	2.6	NA	ND	NA	246
Rubber	0.14	8.1	2.0	1.0	23.0	469.0	NA	30.0	58.0	0.3	NA	6.0	NA	806
Paper	16.47	45.0	1.0	0.6	ND	7.0	NA	79.0	14.0	0.1	NA	ND	NA	88.0
Non-ferrous	2.28	12.2	1.2	0.3	12.0	65.0	NA	6494	1050	ND	NA	178	NA	26700
Foam	0.54	28.0 ²	0.3	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Rock/Concrete	0.97	2.0	0.5	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Glass	9.30	8.1	0.0	ND	ND	ND	NA	ND	84.0	0.2	NA	ND	NA	ND
Bone	1.58	2.0	1.5	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Batteries	0.93	2.0	0.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Ceramic	2.62	2.0	2.6	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Total	100.00		66.4	2.3	3.6	222	NA	290	167	0.4	NA	29.9	NA	315

¹ Adjusted Tchobanoglous et al (1993) residential MSW data by using average secondary residual moisture 28% (Schubert 2005).² Average of 10 samples. 2002 ECF waste audit data (Schubert 2005).³ Schubert and Gannon (2001).⁴ Rugg and Hanna (1992) unless cited. ND - Not detected. Rugg and Hanna (1992) reported zero was used to substitute ND in calculations and detection limits were not reported.⁵ Concentrations are 2000 and 2001 average for uncured compost from First (TransAlta 2001) and 2001 (City of Edmonton 2002) Annual Reports.

Note: NA - Not available. The waste component corresponding to NA was not included in metal concentration calculation.

Appendix E Raw Data for Trace Metal Concentrations in Feedstocks and Compost Samples

Table E-1. Trace metal concentration raw data (mg kg⁻¹, dry weight basis).

Detection Limits	As	Cd	Cr	Co	Cu	Pb	Hg	Mo	Ni	Se	Zn
Paper With Black Ink	<0.4	0.03	2.2	<0.2	<2	<0.2	<0.01	<2	<1	<0.6	4
Paper With Black Ink	<0.4	0.03	2.3	<0.2	<2	<0.2	<0.01	<2	<1	<0.6	5
Paper With Colour Ink	<0.4	0.03	2	<0.2	120	<0.2	<0.01	<2	<1	<0.6	5
Paper With Colour Ink	<0.4	0.04	2	<0.2	130	<0.2	<0.01	<2	<1	<0.6	5
Glossy Paper With Colour Ink	<0.4	0.04	2	2	79	0.8	0.02	<2	<1	<0.6	3
Glossy Paper With Colour Ink	<0.4	0.03	2	2	73	0.7	0.02	<2	<1	<0.6	3
Cardboard With Black Ink	0.7	0.21	11	0.8	36	17	0.09	<2	10	<0.6	62
Cardboard With Black Ink	0.7	0.3	11	0.6	58	17	0.09	4	11	<0.6	69
Cardboard With Colour Ink	<0.4	0.05	1	<0.2	20	1	0.01	67	<1	<0.6	10
Cardboard With Colour Ink	<0.4	0.11	1	<0.2	20	1	0.01	44	<1	<0.6	10
Glossy Cardboard With Colour Ink	<0.4	0.05	3.6	0.8	26	4.8	0.03	<2	<1	<0.6	34
Glossy Cardboard With Colour Ink	<0.4	0.03	2.9	0.8	24	4.8	0.04	<2	<1	<0.6	34
Plastic Without Ink	<0.4	<0.02	<1	<0.2	<2	<0.2	<0.01	<2	<1	<0.6	<2
Plastic Without Ink	<0.4	<0.02	<1	<0.2	<2	<0.2	<0.01	<2	<1	<0.6	<2
Plastic With Colour Ink	<0.4	<0.02	<1	<0.2	10	<0.2	0.01	<2	<1	<0.6	3
Plastic With Colour Ink	<0.4	<0.02	<1	<0.2	9	<0.2	<0.01	4	<1	<0.6	2
Glass With Brown and Yellow Colour	<0.2	<0.01	<0.5	<0.1	<1	<0.1	<0.01	<1	<0.5	<0.3	<1
Glass With Brown and Yellow Colour	<0.2	<0.01	<0.5	<0.1	<1	<0.1	<0.01	<1	<0.5	<0.3	<1
Glass With Blue and Green Colour	<0.2	<0.01	<0.5	<0.1	<1	<0.1	<0.01	<1	<0.5	<0.3	<1
Glass With Blue and Green Colour	<0.2	<0.01	<0.5	<0.1	<1	<0.1	<0.01	<1	<0.5	<0.3	<1

Table E-1. Continued.

	As	Cd	Cr	Co	Cu	Pb	Hg	Mo	Ni	Se	Zn
Detection Limits	0.2	0.01	0.5	0.1	1	0.1	0.01	1	0.5	0.3	1
6.3 mm Sieve Overs	5.2	2.51	63.7	7.3	211	128	0.5	4	52	0.7	567
6.3 mm Sieve Overs	5.1	2.55	64.4	6.7	258	121	0.67	4	51.2	0.8	557
4 mm Sieve Overs	5.2	3.04	78.9	6.2	274	140	0.4	6	55	0.6	607
4 mm Sieve Overs	5.2	3.2	82.9	6.7	280	227	0.53	4	60.1	0.8	649
2 mm Sieve Overs	6.1	3.54	90.8	6.6	301	151	0.5	5	62.7	1	727
2 mm Sieve Overs	6.4	3.46	91.6	7.2	298	502	0.39	5	64.6	1	724
2 mm Sieve Unders	6	3.81	100	7.7	327	169	1.25	6	66.6	1.1	799
2 mm Sieve Unders	5.5	4.27	105	7	311	160	1.27	6	65.3	1.3	764
Plastic Foreign Matter	2	1.15	16	2.9	73	52	1	<2	16	<0.6	214
Glass Foreign Matter	0.4	0.03	1.9	1.7	30	2.3	0.24	<1	1.2	<0.3	12
Metal Foreign Matter	6	2.52	39	4	260	70	NA	10	48	<3	500
Sorted Compost Portion	5.5	2.46	44.2	5.4	152	118	0.35	3	50.1	0.6	516

NA - Not available.

Appendix F Raw Data for Sieve Analysis

"S" in Tables F-1 to F-4 indicates particle size of each sieved compost fractions.

Table F-1. Sieve analysis, moisture content, and dry weight percentage results for unscreened compost product.

Particle size, mm	Wet weight, g			Moisture content, %			Dry weight, g		
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
S > 9.5	119.93	74.49	87.06	31.10	30.82	30.96	82.63	51.53	60.11
9.5 > S > 6.3	71.31	56.69	59.58	33.02	33.20	33.12	47.76	37.87	39.85
6.3 > S > 4.0	73.68	63.31	62.88	37.49	37.18	37.33	46.06	39.77	39.40
4.0 > S > 2.0	127.97	117.82	119.76	38.54	38.50	38.52	78.65	72.46	73.63
2.0 > S > 0.85	210.91	184.81	185.88	38.70	38.65	38.68	129.29	113.38	113.99
S < 0.85	103.79	81.07	84.84	38.89	38.91	38.90	63.43	49.53	51.84
Total	707.59	578.19	600.00	36.71	36.95	36.86	447.82	364.54	378.82

Table F-1. Continued.

Particle size, mm	%, dry weight				
	Sample 1	Sample 2	Sample 3	Average	%RSD
S > 9.5	18.45	14.14	15.87	16.15	13.45
9.5 > S > 6.3	10.67	10.39	10.52	10.52	1.32
6.3 > S > 4.0	10.28	10.91	10.40	10.53	3.16
4.0 > S > 2.0	17.56	19.88	19.44	18.96	6.48
2.0 > S > 0.85	28.87	31.10	30.09	30.02	3.72
S < 0.85	14.16	13.59	13.68	13.81	2.24
Total	100.00	100.00	100.00	100.00	0.00

Table F-2. Sieve analysis, moisture content and dry weight percentage results for unscreened compost product (< 6.3 mm fractions).

Particle size, mm	Wet weight, g			Moisture content, %			Dry weight, g		
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
6.3 > S > 4.0	73.68	63.31	62.88	37.49	37.18	37.33	46.06	39.77	39.40
4.0 > S > 2.0	127.97	117.82	119.76	38.54	38.50	38.52	78.65	72.46	73.63
2.0 > S > 0.85	210.91	184.81	185.88	38.70	38.65	38.68	129.29	113.38	113.99
S < 0.85	103.79	81.07	84.84	38.89	38.91	38.90	63.43	49.53	51.84
Total	516.35	447.01	453.36	38.53	38.45	38.49	317.42	275.14	278.86

Table F-2. Continued.

Particle size, mm	%, dry weight				
	Sample 1	Sample 2	Sample 3	Average	%RSD
6.3 > S > 4.0	14.51	14.46	14.13	14.37	1.43
4.0 > S > 2.0	24.78	26.34	26.40	25.84	3.56
2.0 > S > 0.85	40.73	41.21	40.88	40.94	0.60
S < 0.85	19.98	18.00	18.59	18.86	5.40
Total	100	100	100	100.00	0.00

Table F-3. Sieve analysis, moisture content and dry weight percentage results for screened compost product.

Particle size, mm	Wet weight, g		Moisture content, %		Dry weight, g	
	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
S > 9.5	3.05	2.98	31	31	0.10	0.07
9.5 > S > 6.3	3.67	2.9	33.1	33.1	0.52	0.00
6.3 > S > 4.0	39.24	46.49	38.31	38.08	22.42	27.00
4.0 > S > 2.0	130.77	150.21	38.71	38.37	78.38	90.79
2.0 > S > 0.85	250.7	265	39.37	39.32	150.25	159.04
S < 0.85	64.9	50.6	39.84	39.75	37.30	28.75
Total	492.33	518.18	41.31	41.02	288.97	305.65

Table F-3. Continued.

Particle size, mm	%, dry weight				
	Sample 1	Sample 2	Average	StDev	%RSD
S > 9.5	0.04	0.02	0.03	0.01	32.07
9.5 > S > 6.3	0.18	0.00	0.09	0.13	141.42
6.3 > S > 4.0	7.76	8.83	8.30	0.76	9.17
4.0 > S > 2.0	27.12	29.70	28.41	1.82	6.42
2.0 > S > 0.85	52.00	52.03	52.01	0.03	0.05
S < 0.85	12.91	9.41	11.16	2.48	22.19
Total	100.00	100.00	100.00	0.00	0.00

Table F-4. Sieve analysis, moisture content and dry weight percentage results for screened compost product (< 6.3 mm fractions).

Particle size, mm	Wet weight, g		Moisture content, %		Dry weight, g	
	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
6.3 > S > 4.0	39.24	46.49	38.31	38.08	22.42	27.00
4.0 > S > 2.0	130.77	150.21	38.71	38.37	78.38	90.79
2.0 > S > 0.85	250.7	265	39.37	39.32	150.25	159.04
S < 0.85	64.9	50.6	39.84	39.75	37.30	28.75
Total	485.61	512.3	40.62	40.35	288.35	305.58

Table F-4. Continued.

Particle size, mm	%, dry weight				
	Sample 1	Sample 2	Average	StDev	%RSD
6.3 > S > 4.0	7.77	8.83	8.30	0.75	9.03
4.0 > S > 2.0	27.18	29.71	28.45	1.79	6.29
2.0 > S > 0.85	52.11	52.05	52.08	0.04	0.08
S < 0.85	12.94	9.41	11.17	2.49	22.33
Total	100.00	100.00	100.00	0.00	0.00